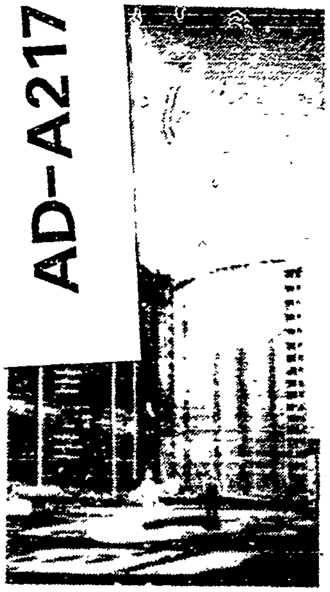
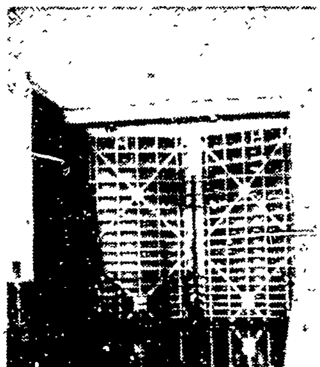
(2)

US Army Corps of Engineers





REMR RESEARCH PROGRAM

REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-OM-6

NETWORK LEVEL REMR MANAGEMENT SYSTEM FOR CIVIL WORKS STRUCTURES: CONCEPT DEMONSTRATION ON INLAND WATERWAYS LOCKS

by

Michael J. Markow, Sue McNeil,
Dharma Acharya, and Mark Brown

Center for Construction Research and Education
Department of Civil Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

US ARMY CORPS OF ENGINEERS
CERL
CONSTRUCTION ENGINEERING RESEARCH LABORATORY

December 1989
Final Report

Approved For Public Release; Distribution Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000
Under Contract No. DACA88-86-D-0013
Under Civil Works Research Work Unit 32337

Monitored by US Army Construction Engineering
Research Laboratory
PO Box 4005, Champaign, Illinois 61824-4005

The following two letters used as part of the number designating technical reports of research published under the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program identify the problem area under which the report was prepared:

	Problem Area		Problem Area
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

COVER PHOTOS:

TOP - Concrete lockwall at Port Allen Lock, Intercoastal Waterway, LA.

BOTTOM - Miter gate at Port Allen Lock, Intercoastal Waterway, LA.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No 0704-0188 Exp Date Jun 30 1986

1a REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S)	5 MONITORING ORGANIZATION REPORT NUMBER(S): Technical Report REMR-OM-6
6a NAME OF PERFORMING ORGANIZATION: See reverse. / 6b OFFICE SYMBOL (If applicable)	7a NAME OF MONITORING ORGANIZATION: US Army Construction Engineering Research Laboratory
6c. ADDRESS (City, State, and ZIP Code): Cambridge, MA 02139	7b ADDRESS (City, State, and ZIP Code): PO Box 4005, Champaign, IL 61824-4005
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: US Army Corps of Engineers / 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: Contract No. DACA88-86-D-0013
8c. ADDRESS (City, State, and ZIP Code): Washington, DC 20314-1000	10 SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO / PROJECT NO / TASK NO / WORK UNIT ACCESSION NO 32337

11 TITLE (Include Security Classification)
Network Level REMR Management System for Civil Works Structures: Concept Demonstration on Inland Waterways Locks (U)

12 PERSONAL AUTHOR(S)
Markow, Michael J.; McNeil, Sue; Acharya, Dharma; and Brown, Mark

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM ____ TO ____	1989, December	243

16 SUPPLEMENTARY NOTATION A report of the Operations Management problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	
13	02		REMR; Network Level Management System; Life cycle costs; Civil engineering; Maintenance management
15	01		

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

The objective of this project is to develop a Network Level Management System for the maintenance and rehabilitation of the US Army Corps of Engineers civil works. The Network Management System is based on a life-cycle analysis of the performance and costs of facilities through some analysis period, as affected by REMR policy. The implementation of life-cycle analyses of facilities requires a new approach to looking at facility performance and the factors which influence costs throughout its service life. This approach is referred to as "demand responsive," in that maintenance and rehabilitation

(Cont'd)

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED
22a NAME OF RESPONSIBLE INDIVIDUAL: Gloria J. Wienke	22b TELEPHONE (Include Area Code): (217)352-6511 ext 353 / 22c OFFICE SYMBOL: CECER-IMT

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

BLOCK 6a. (Cont'd)

Center for Construction Research and Education
Department of Civil Engineering
Massachusetts Institute of Technology

BLOCK 19. (Cont'd)

are viewed as responses to the demand for repair or renewal of the facility. Treating REMR actions as demand-responsive activities requires that three additional elements be introduced within existing planning and management models: 1)

a. Estimates of future resource requirements and costs of managing facilities based on predictions of structural and operational deficiencies caused by use, environment, and age; 2)

b. Clear statements of REMR policies themselves, defining the types of preventive or corrective actions to be taken, and when and where they are to ~~commence~~. start; and 3)

c. Relationships between the as-maintained state of the civil facility, and the impacts on both the Corps and ~~the~~ users of the facility (in terms of preservation of facility investment, the costs, time, and reliability of transportation service provided, safety, etc.), providing a measure of the benefits (or disbenefits) of each policy at the costs computed above.

This report explains the concepts involved in applying life-cycle costing to analyses of REMR policies. Considering locks specifically, it then develops example models of facility performance for lock gates, walls, and mechanical equipment, relates this performance to the costs and the impacts of different REMR policies, and builds these models within a prototype version of a microcomputer-based REMR Management System. The prototype system is then applied to several examples to demonstrate the application of demand-responsive maintenance concepts to realistic problems, to illustrate the system features and procedures, and to explain the results and their interpretation.

PREFACE

This study was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), as part of the Operations Management problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The work was performed under Work Unit 32337, "Implementation of the REMR Management System," for which Dr. Anthony M. Kao, US Army Construction Engineering Research Laboratory (USACERL), was Principal Investigator. Mr. James E. Crews (CECW-OM) was the REMR Technical Monitor for this work.

Mr. Jesse A. Pfeiffer, Jr., was the REMR Coordinator at the Directorate of Research and Development, HQUSACE; Mr. James E. Crews and Dr. Tony C. Liu served as the REMR Overview Committee; Mr. William F. McCleese, US Army Engineer Waterways Experiment Station, was the REMR Program Manager; Dr. Kao was also the Problem Area Leader for the Operations Management problem area.

This study was performed under Contract/Purchase Order No. DACA88-86-D-0013 with Massachusetts Institute of Technology (MIT), Cambridge, Mass., and was conducted by Mr. Michael J. Markow (Principal Investigator), under the direct guidance of Dr. Kao. General supervision was provided by Dr. R. Quattrone, Chief of USACERL's Engineering and Materials (EM) Division. Preparation of the draft was supervised by Mrs. Irene Miller of MIT. The Technical Editor was Gloria J. Wienke, USACERL Information Management Office.

COL Carl O. Magnell was Commander and Director of USACERL during this research, and Dr. L. R. Schaffer was the Technical Director.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CONVERSION FACTORS, NON-SI TO SI (MET· ·'
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be convert· ᵌ to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
miles (US statute)	1.609347	kilometres
square feet	0.09290304	square metres
tons (2,000 pounds, mass)	907.1847	kilograms

NETWORK LEVEL REMR MANAGEMENT SYSTEM FOR CIVIL WORKS STRUCTURES: CONCEPT DEMONSTRATION ON INLAND WATERWAYS LOCKS

PART I: INTRODUCTION

Background: The REMR Program

1. The work described in this report has been sponsored by the US Army Construction Engineering Research Laboratory (USACERL), as part of the Army's Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The REMR Program was established to address the growing need to keep civil works under the jurisdiction of the US Army Corps of Engineers (CE) in safe, working condition. A report outlining the significance of these needs, as well as related mission objectives, identification and assessment of problems, research requirements and benefits, and proposed program schedule and costs was prepared by the US Army Engineer Waterways Experiment Station (WES) in 1983 (Scanlon et al. 1983).

2. Recognition of the need for the REMR Program actually grew out of Corps of Engineers workshops devoted to the design and construction of new hydraulic structures. To quote: "In the past, when a structure or project reached the point of requiring drastic REMR measures to keep it functioning, it was generally also time to replace it with a larger project" (Scanlon et al. 1983). Thus, the Corps has not had to deal with large-scale programs involving existing, old facilities. However, once it was realized that "the technology needed for designing and constructing new hydraulic structures is not the same technology needed for repairing, evaluating, maintaining, and rehabilitating existing hydraulic structures and projects," the rationale for the REMR program became clear.

3. This rationale is supported by statistics indicating the growing importance of maintenance, repair, and rehabilitation as compared to new construction. For example, operations and maintenance have consumed rapidly increasing shares of total Corps appropriations for civil works, as indicated in Table 1 (Scanlon et al. 1983). Similar trends are displayed in Tables 2 and 3 (CE 1979) (although the two sets of figures for FY 1974 do not

Table 1

Percentages of Civil Works Appropriations

Devoted to Operations and Maintenance Versus New Construction

Year	O & M (%)	Construction (%)
1967	16	79
1970	24	66
1977	28	65
1980	35	56
1983 (est.)	40	46
1985 (proj.)	50	--

correspond, likely due to different line items or definitions of facilities used in the respective estimates).

4. In response to the growing importance of facility operations and maintenance, the REMR program has as its objective to perform research on the evaluation, maintenance, repair, and rehabilitation of existing civil works. Among the benefits expected from this program are the following:

- a. To permit more economical, rapid, and quality-oriented performance of REMR activities.
- b. To increase the service life of facilities, so long as it remains reasonable and feasible to do so.
- c. To correct operational problems so that they do not recur within the near future.
- d. To modify, if appropriate, design and construction procedures to reduce later problems with facilities associated with REMR.
- e. To disseminate knowledge to other agencies involved in REMR activities.

Scope: Facilities To Be Addressed

5. REMR activities encompass various civil works projects involving locks, dams, coastal facilities, inland and coastal waterways, power structures, and multipurpose projects. These facilities serve many functions, including flood control, navigation, hydropower, water supply, natural resource management, and recreation. Thus, the REMR agenda is very broad. By

Table 2

Corps of Engineers Navigation Expenditures in Millions of Current Dollars

	1974		1975		1976	
	O&M*	Construction	O&M	Construction	O&M	Construction
Shallow draft inland and intracoastal waterways	136	257	137	282	146	240
Shallow draft harbors and channels	17	12	13	9	17	11
Great Lakes harbors	25	8	58	6	47	3
Deep draft harbors and channels	105	34	124	39	134	43
Small boat harbors	11	--	7	1	8	--
Total	295	311	339	338	352	297

Source: Corps of Engineers, Construction-Operations Division--Civil Works. This information was supplied by the Corps at CBO's request. Decisions on how to define each class and which expenditures to include were made by the Corps. It should be noted that construction expenditures include a portion of the costs of multipurpose projects; the allocation is based on the Corps' experience with its official method of allocating the joint costs of such projects.

*Operations and Maintenance

Table 3

Corps of Engineers Expenditures by Major Account for Commercial Navigation on the Inland and Intracoastal Waterways (in thousands of dollars)

Parameter	FY 1965	FY 1970	FY 1974	10-Year Total FY 1965-1974
Construction				
Mississippi River and tributaries	11,894	10,970	21,619	139,969
Advanced engineering and design	2,345	1,792	2,734	26,500
Channel improvements	40,276	28,655	27,489	324,094
Locks and dams	130,701	122,057	129,603	1,364,228
Multipurpose (w/power)	32,267	36,215	41,481	417,952
Rehabilitation	556	---	---	4,205
Total	218,039	199,689	222,926	2,276,948
Operation and Maintenance costs				
Mississippi River and tributaries	6,709	7,217	10,050	73,645
Channel improvements	23,990	32,840	45,190	314,540
Locks and dams	29,647	46,741	87,676	488,665
Multipurpose (w/power)	3,800	6,973	12,964	72,315
Total	64,146	93,771	155,880	949,165
Total Construction and Operation and Maintenance	282,185	293,460	378,806	3,226,113

Note: Figures do not include non-CE federal expenditures.

Source: Association of American Railroads, *Inland Waterway User Charges*, Working Paper 75-3, Washington, DC, September 1985, Table 2.

encompassing the several categories of civil works above, it includes structures of diverse characteristics in engineering design and construction, materials, operating requirements and environments, and REMR needs and costs.

6. In light of this diverse and extensive system of projects, this research is limited to one class of structure: locks used in inland waterway navigation. This approach allows more detailed exploration and full development of the engineering, economic, technological, and management principles and relationships needed to address facility maintenance and rehabilitation for this type of structure. (Even with this limitation, we should note that locks throughout the country have significantly different dimensions, capacities, and structural and operational features.) Once the applicable concepts, principles, analytic methods, and computer software have been developed and demonstrated for locks, they can be extended and adapted to other civil works within the Corps' inventory.*

Importance of locks

7. Several reasons support the choice of locks as the focus of the initial stages of this work. Not only are they of technical interest, comprising various concrete, steel, and mechanical components of importance to the REMR effort, but they also are key (and highly visible) elements of the inland waterway transportation network. The importance of this network to the Nation lies in three areas (National Waterways Study 1983):

a. Responsiveness to defense mobilization.

b. Capacity to accommodate commercial traffic.

c. Reliability, safety, and efficiency of commodity transportation.

Defense mobilization

8. Locks, dams, and inland waterways serve strategic objectives for National defense, and provide transportation alternatives in a national or regional emergency. They are best suited to movement of bulk commodities (e.g., coal, ore, fuel) and could be used to transport vital goods (e.g., steel, aluminum) to and from strategic industries, military bases, and ports.

---

* Navigation locks are found at project sites that also include dams to maintain the required difference in elevation between the upstream and downstream pool. Therefore, in many instances in this report, a project is referred to by its proper designation, "lock(s) and dam." However, the focus of the research will be on the gates, walls, and machinery that constitute the lock itself.

For example, during World War II the inland waterways provided a safe and effective route for transporting essential petroleum products from the Gulf region to East Coast refineries. In fact, the relatively safety (i.e., protection from enemy submarines) of industrial sites on the inland waterways and Great Lakes has influenced the locating of defense-related plants (National Waterways Study 1983). Inland waterways could also be used in non-defense emergencies (Scanlon et al. 1983).

Commerce

9. From a commercial perspective, waterways will likely continue to serve as major links for shipping bulk commodities. The National Waterways Study forecasts an increase in total US waterborne traffic from 1,915 million tons* in 1977 to a maximum of 2,890 million tons by 2003. As of 1980, domestic commerce accounted for just over one-half of total waterborne traffic, or 1,078 million tons. Of that share, the inland waterways carried 535 million tons, with the remainder served by coastal and lake movements. Major commodities transported on the inland waterways are listed in Table 4 (National Waterways Study 1983).

Quality of service

10. As a mode of transportation, the inland waterways have proven to be safe, efficient, and reliable. However, "the continued effectiveness of US waterways and ports may be seriously impaired in the near future by the increasing age of structures, technological obsolescence in the system, and basic physical limitations at strategic points along several principal

Table 4

Major Commodities Using Inland Waterways (1980)

Rank	Commodity	Millions of Tons	Percent of Total
1	Coal	131.6	24.6
2	Petroleum Products	101.5	19.0
3	Selected Grains	59.1	11.0
4	Crude Petroleum	41.6	7.8
5	All Other	201.2	37.6
Total		535.0	100.0

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 8.

waterways" (National Waterways Study 1983). The identification of how lock maintenance, repair, and rehabilitation may affect waterway system service and reliability is one aspect of the research to be performed in this project.

Objective

11. The objective of this research is to develop a network level management system for the evaluation, maintenance, repair, and rehabilitation of civil works under the jurisdiction of the Corps of Engineers. The initial stages of this work will focus on locks on the inland waterways network. Once the management system has been demonstrated for locks, however, these concepts of maintenance management can be extended, adapted, and applied to other facilities within the REMR program.

12. This report documents progress during the initial phase of work to design and develop the management system. It discusses the concepts applicable to the planning, assessment, budgeting, and management of REMR activities, the analytic requirements of models for evaluating, maintaining, repairing, and rehabilitating facilities, and data available to support these predictive and cost models. The findings in this report may be the subject of further research through other research programs. In Part V the findings are incorporated within a prototype of the management system, to illustrate its operation and the interpretation of its results.

Facility Characteristics

General information

13. There are 25,500 miles of commercially navigable waterways in the United States, including 15,000 miles of inland waterways, and 10,500 coastal waterways (US Congress 1977). These waterways are served by commercial ports operated by private industry or by local or state governments. Navigation improvements and their operation and maintenance are, for the most part, under the jurisdiction of the Corps of Engineers and include locks, dams, channel alignments, bank stabilization, cutoffs, dredging, and clearing and snagging operations.

14. Locks and dams are essential for creating stepped navigational pools with reliable depths for navigation. However, if not maintained properly, these structures can become major constraints to the continued growth of waterborne traffic. In raising or lowering vessels from one navigation pool to the next, locks require a certain amount of time to service vessels; if this time increases due to malfunctioning lock components, queues may develop in busy channels, leading to costly delays. Furthermore, if a main lock must be closed unexpectedly to allow dewatering and repair, traffic may be severely congested and delayed (if a [generally smaller] auxiliary lock is available) or impeded (if no auxiliary lock is available). By maintaining the structural and operational integrity of the locks, REMR activities are important in sustaining efficient and reliable transportation service on the waterways.

15. Analysis of REMR policy alternatives requires data on the physical and historical characteristics of the waterways structures. One of the first tasks of this project was to identify what data were available on the dimensions, conditions, traffic, REMR policies and activities, and costs related to locks. A review was made of different data bases already developed and managed by the Corps of Engineers. Field visits and interviews were also conducted, and reports and files collected from various sites. This process is still underway and will continue throughout the design of the facility management system. In this report the major sources of data already identified are described, and some preliminary analyses of the contents of selected data files are presented.

Geographic distribution

16. Civil works under the jurisdiction of the Army Corps of Engineers are divided among 11 Divisions and 36 Districts nationwide. The boundaries and designations of these Districts and Divisions are shown in Figure 1.

17. Based on the facilities database compiled by the Army Corps of Engineers has about 593 locks and dams. Physical descriptions of these locks and dams used in this research were based upon compilations by the WES. Example listings for two facilities are shown in Figure 2. These data were used to produce statistical summaries represented in the next series of figures.

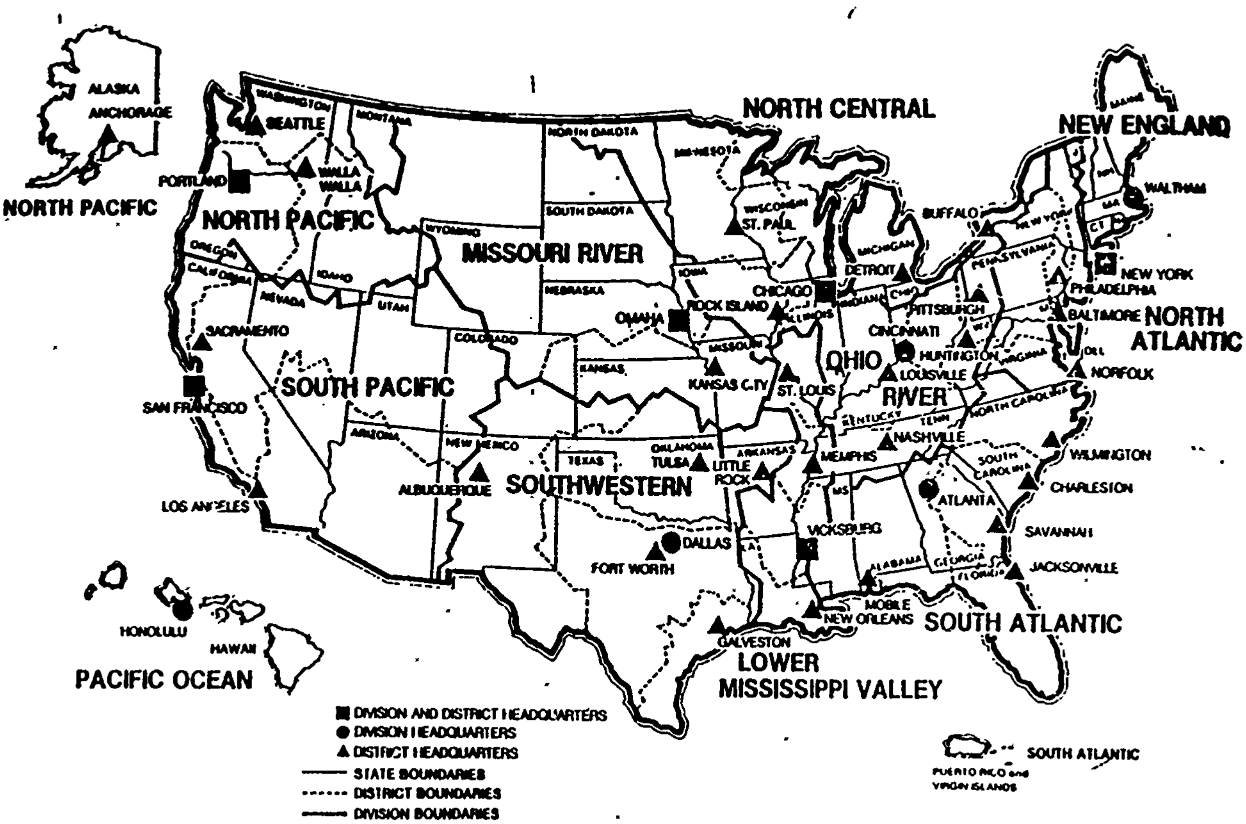


Figure 1. Corps of Engineers Divisions and Districts for civil works

18. The geographic distribution of locks and dams is illustrated in Figure 3.* Three Divisions--Ohio River, North Central, and Southwest--dominate for this type of facility, although the works in this category in the Southwest Division comprise primarily dams, not locks. For this reason, our research has focused to date on conditions prevalent in the Ohio River and North Central Divisions. As work continues and extends to other types of facilities, a wider geographic view will need to be taken.

19. The functions of these facilities are given in Figure 4. The frequencies indicated by the bars in Figure 4 sum to a value greater than 100 percent because facilities may serve more than one purpose. The dominant uses of locks and dams are for flood control, recreation, and navigation (with recreation likely secondary to one of the other purposes). Figure 4 reinforces the earlier contention that the navigational impacts of REMR activities

* Where a facility consists of both locks and dam, it is counted only once.

ORL. Wes Listing of Hydraulic Structures - Detailed Report by District

----

```
     Structure Name: OHIO RIVER LOCK AND DAM #53
       Project Name: OHIO RIVER
          Lake Name:
              River: OHIO RIVER
        Mile Number:
    Downstream City: OLMSTED, IL

           Category: CORPS                Owner: DAEN ORL
           District: ORL               Operator: DAEN ORL
              State: KY          Year Completed: 1929
       Seismic Zone: 3        Downstream Hazard: 3

          Number of Lock Chambers: 1
                     Type of Dam: O
                        Purposes: N
                Type of Spillway: NONE
                  Type of outlet:
           Structure Height(FT):       33
               Crest length(FT):     3928
  Max Storage Capacity(ACRE-FT):   388170
          Spillway Discharge(CFS):
```

ORL Wes Listing of Hydraulic Structures - Detailed Report by District

----

```
     Structure Name: OHIO RIVER LOCKS AND DAM #52
       Project Name: OHIO RIVER
          Lake Name:
              River: OHIO RIVER
        Mile Number:   42.1
    Downstream City: METROPOLIS, IL

           Category: CORPS                Owner: DAEN ORL
           District: ORL               Operator: DAEN ORL
              State: KY          Year Completed: 1969
       Seismic Zone: 3        Downstream Hazard: 3

          Number of Lock Chambers: 2
                     Type of Dam: O
                        Purposes: N
                Type of Spillway: NONE
                  Type of outlet:
           Structure Height(FT):       36
               Crest length(FT):     3218
  Max Storage Capacity(ACRE-FT):   339600
          Spillway Discharge(CFS):
```

Figure 2. Example lock and dam data

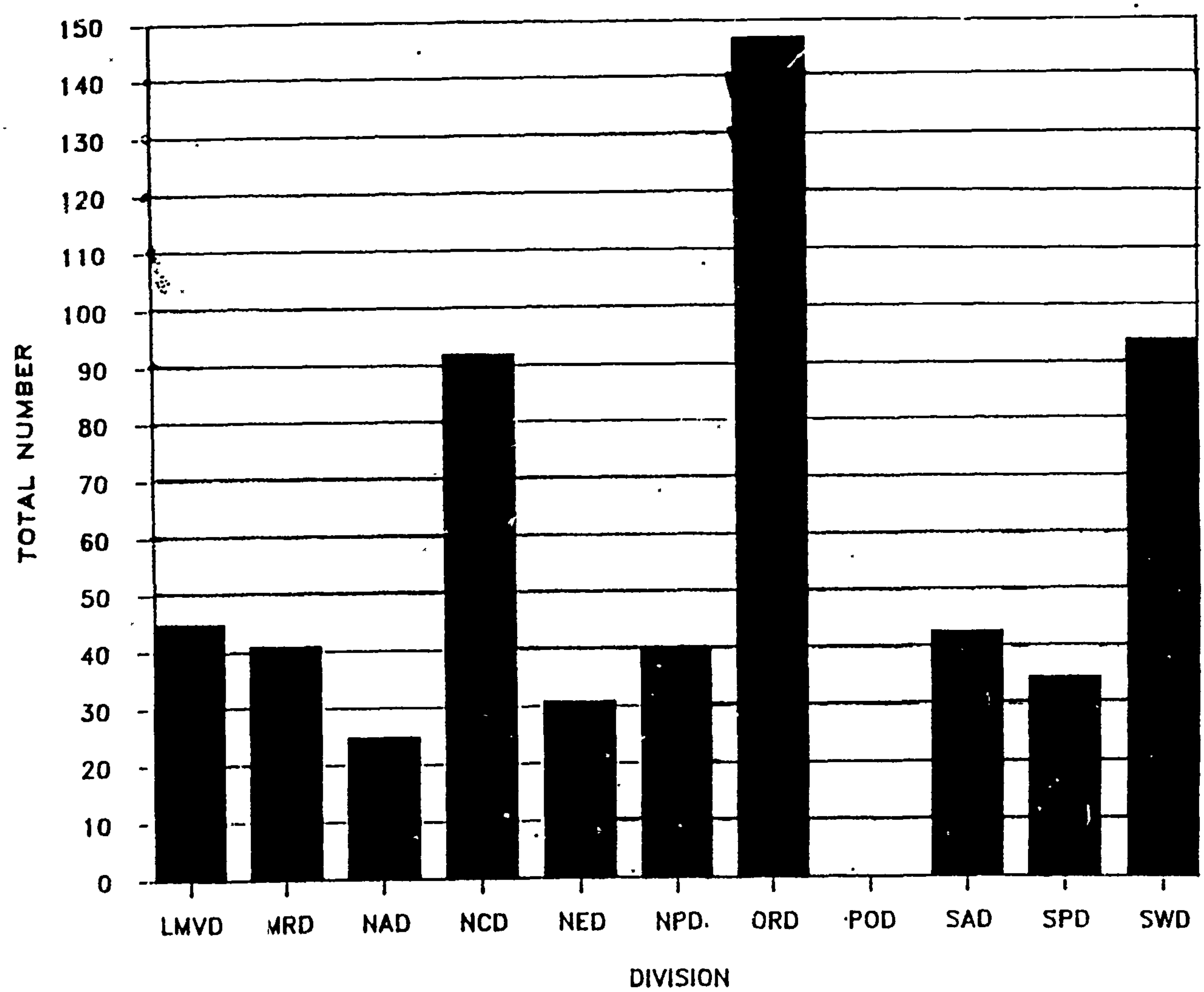


Figure 3. Distribution of locks and dams by Division

for locks represent a major political and economic issue. A major component of this research is, therefore, to identify and analyze the impacts (or consequences) of REMR activities on navigational efficiency, reliability, and cost.

Condition and age distribution

20. Facilities deteriorate over time in their structural and operational performance, and it is this deterioration that generates the need for REMR projects. Despite the importance of information about facility condition, the

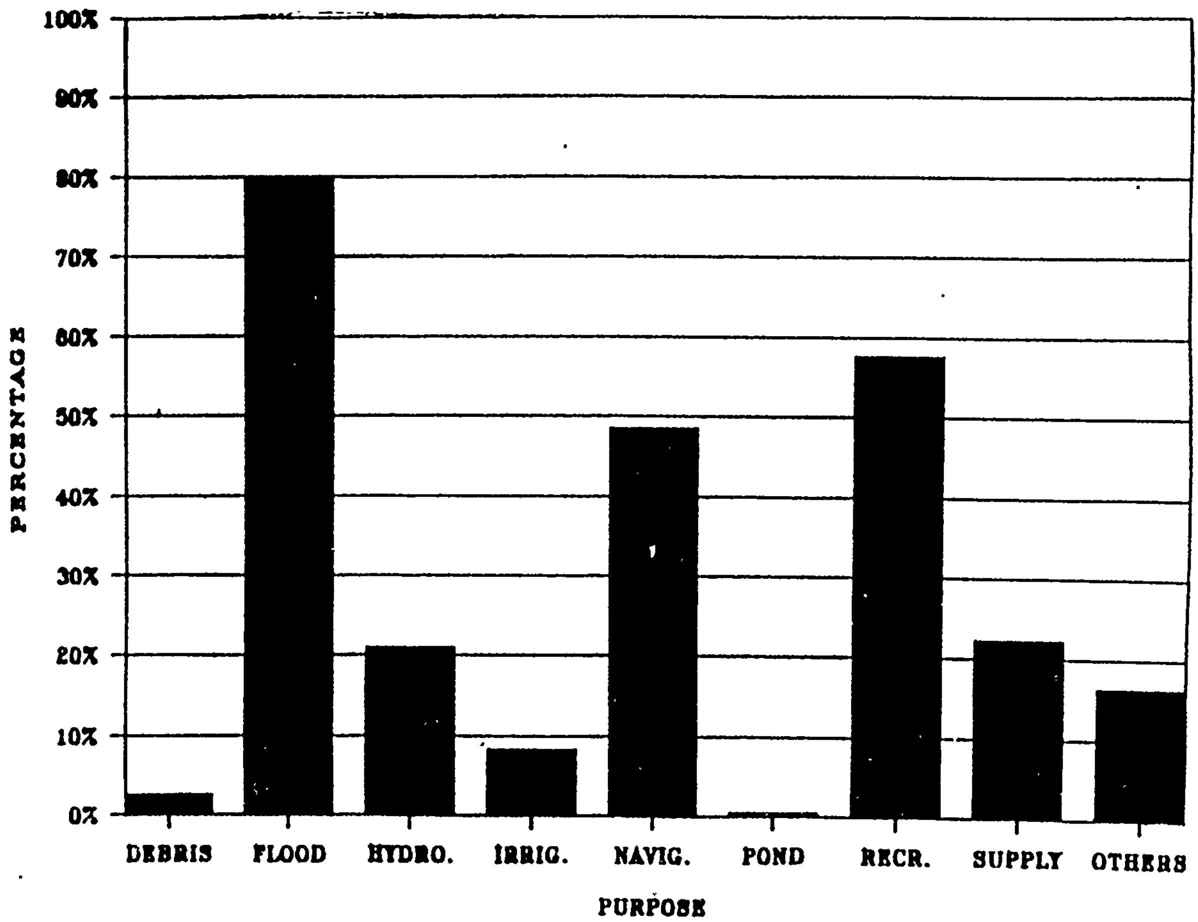


Figure 4. Distribution of locks and dams by purpose

quantification of condition values and compilation of trends of facility condition over time are only now beginning to be addressed by the Corps. Although periodic inspections have been performed at individual facilities for at least 20 years, records of deterioration are qualitative or pictorial: They identify broad needs and may contribute to the justification of repair or rehabilitation projects, but do not by themselves provide a detailed, precise record of the progression of damage in the various components of a facility.

As an example, the data in Figure 2 include no mention of facility condition or changes in its operations (e.g., reliability, frequency of breakdowns, annual downtime, and long-term trends in these factors).

21. The concepts of condition measurement, the definition of appropriate indices, and the specification of methods, procedures, and technologies to assess facility conditions are the subjects of several research projects now being sponsored by USACERL, and the findings of these companion research efforts are expected to complement the results of this study. When they become available for practice in a few years, these results should help the Corps to quantify current REMR needs and to plan for future work.

22. Even without condition data, it is possible to get some aggregate understanding of the composition of the locks and dams inventory by studying its age distribution. Age is an imperfect surrogate for condition, since facility deterioration depends upon the standard of design, quality of initial construction, amount and type of use, operating environment (e.g., weather and water chemistry), and past maintenance performed. Nevertheless, given that one can ascribe reasonable design lives to facilities and that requirements for both corrective and preventive maintenance may increase with age, facility age provides a reasonable basis for judging at least relative changes in REMR needs.

Overall trends

23. The distribution of ages for 593 locks and dams is shown in Figure 5, covering all divisions. Several trends are immediately apparent:

a. The inventory of facilities will begin to age much faster than it has in the past. Assume, for the sake of argument, that the design lives of key components of locks and dams are 50 years. The total number of facilities now exceeding 50 years' age is 85. Yet, in the next decade that number will be more than doubled, with the addition of 109 facilities now 41 to 50 years old.

b. Once this more rapid aging begins, it will continue for at least four decades, as facilities built within the past 40 years are continually added to the "over 50" portion of the inventory.

c. In the past, aging has been dealt with by building new, larger facilities. The problem now is one of maintaining, repairing, and rebuilding existing facilities as they approach the end of their useful lives. The implications of these aging trends are that the requirements for REMR activities for locks and dams will increase significantly in the coming decade, and this

increased level of activity will be sustained for several decades thereafter.

Variations within divisions

24. The age distribution will not affect Corps Divisions uniformly. To illustrate the different impacts that may be expected, graphs for the North Central, Missouri River, and Ohio River Divisions are shown in Figures 6 through 8, respectively. Patterns within the other divisions may then be discussed with respect to these examples.

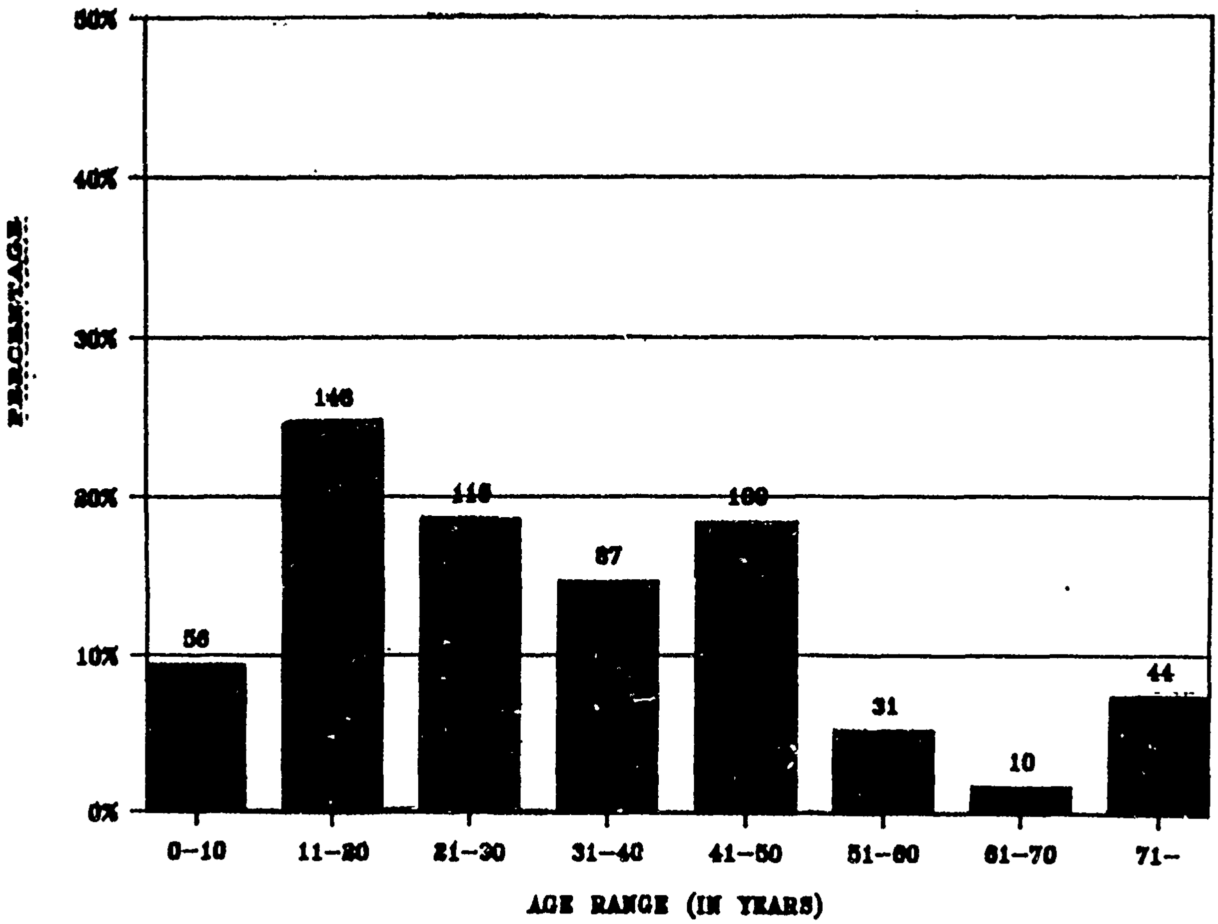


Figure 5. Age distribution of locks and dams, all Divisions

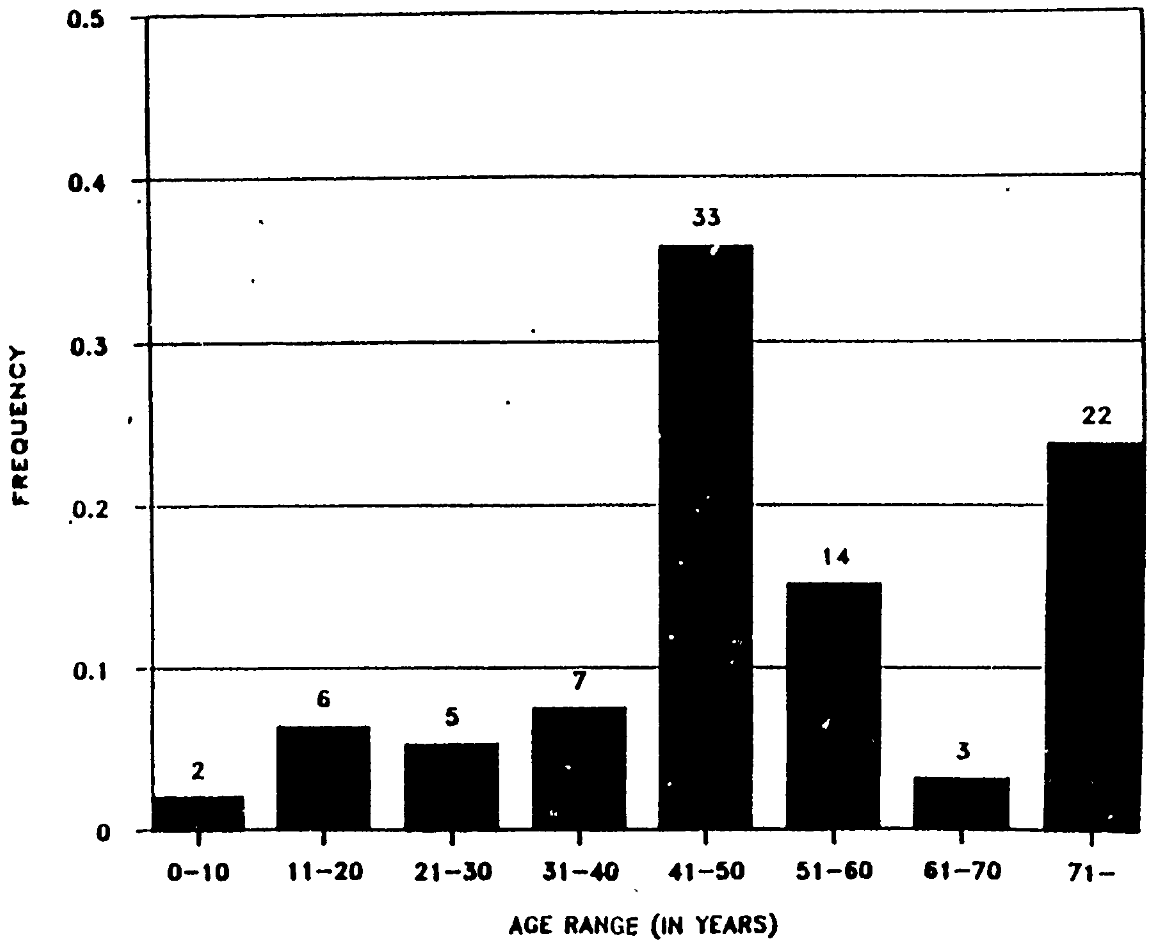


Figure 6. Age distribution of locks and dams, North Central Division

25. The majority of facilities in the North Central Division are over 50 years old (Figure 6). Although this distribution may imply some significant needs for REMR (which may already have become apparent), it also implies a degree of stability in the long-term trend of system expenditures: i.e., the system is already old and will simply age further, perhaps necessitating increases in REMR funding, but no sudden jumps should occur until major rehabilitation or reconstruction of the exhausted facilities takes place. With this aged set of facilities, the North Central Division is not typical of other Corps Divisions.

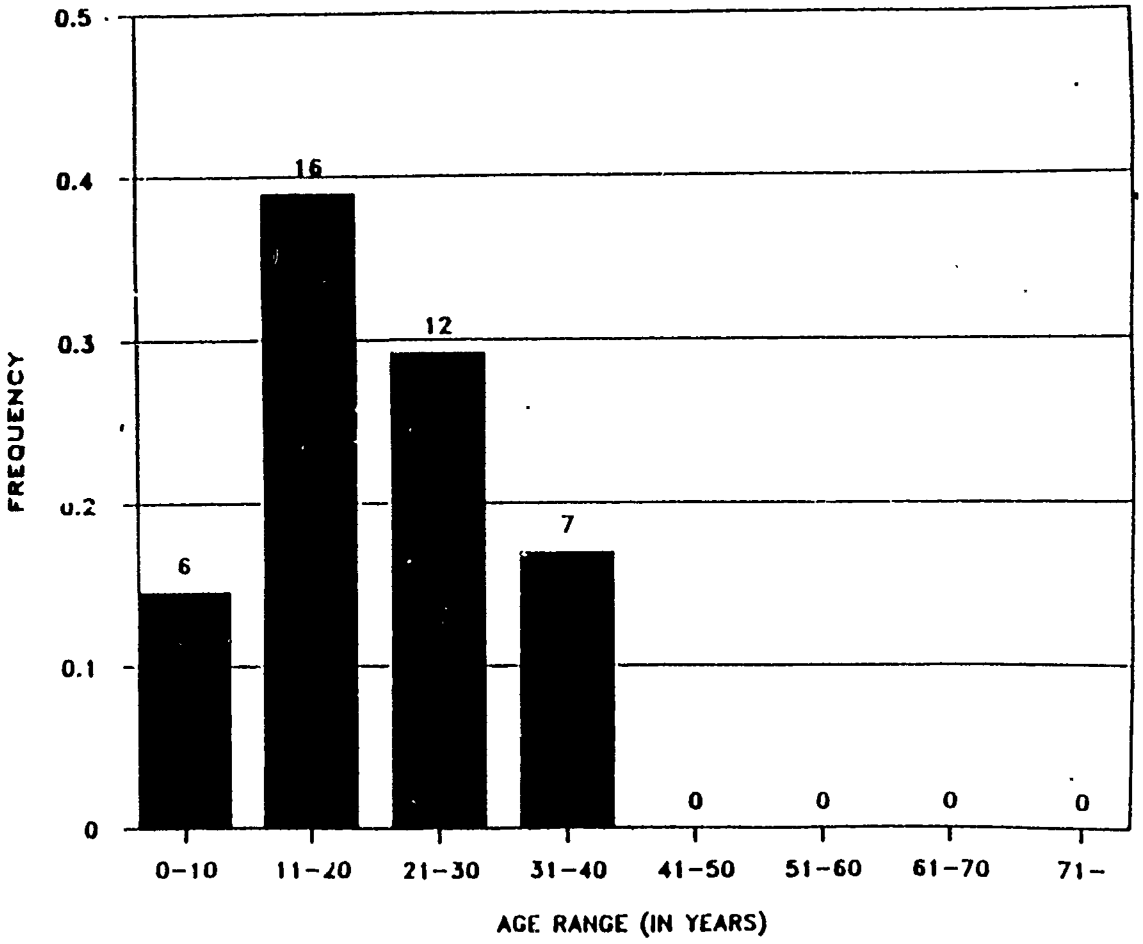


Figure 7. Age distribution of locks and dams, Missouri River Division

26. The Missouri River Division manages a comparatively young population of dams (no locks), with no facility more than 40 years old (Figure 7). The Ohio River Division, by comparison, encompasses a spectrum of ages, ranging from newly constructed works to those beyond 70 years of service (Figure 8). Most of the other Divisions within the Corps oversee facilities with age distributions similar to Figures 7 and 8, generally with newer works outnumbering the older facilities. In these cases, there is the chance of major increases in REMR needs over the coming years, as facilities reach and exceed

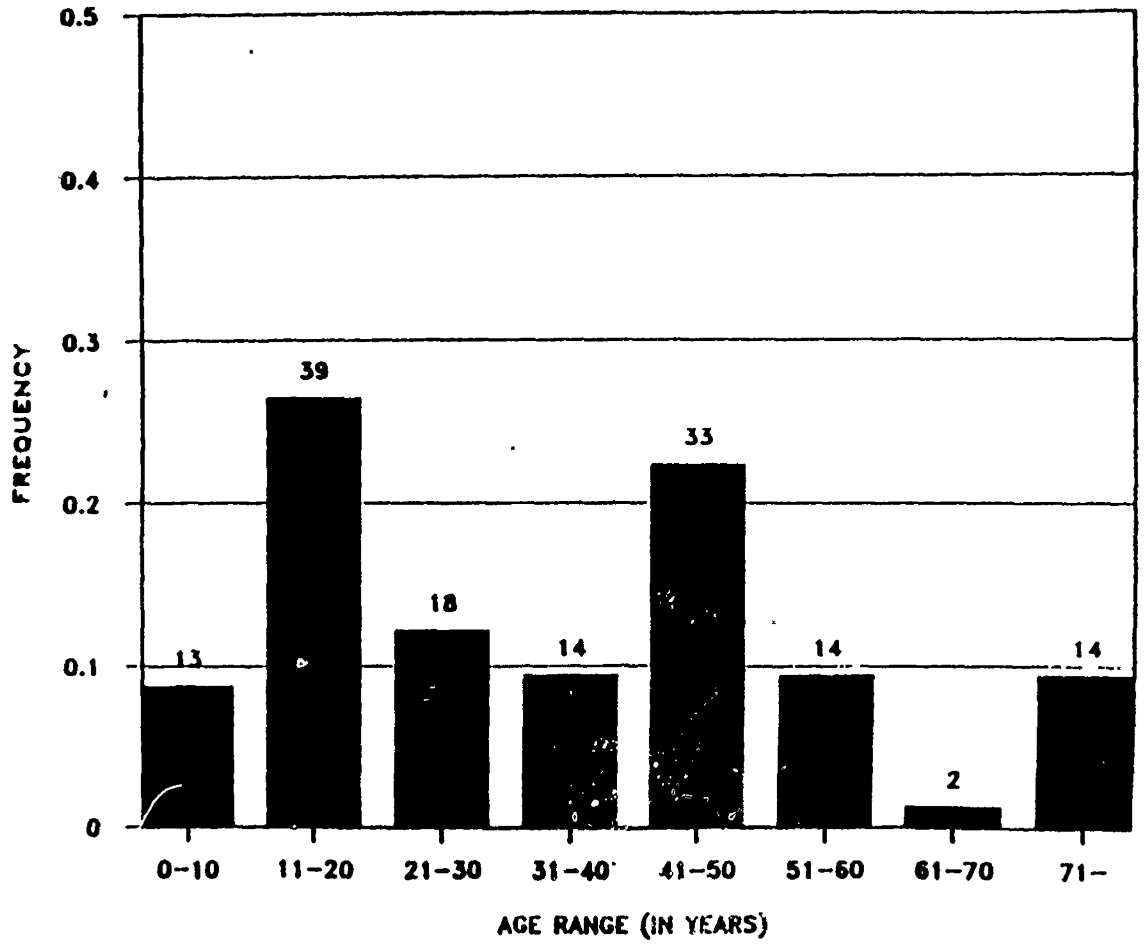


Figure 8. Age distribution of locks and dams, Ohio River Division

their design service lives. Models to predict these changing needs (as functions not only of age, but also traffic use, environment, design and construction characteristics, etc.) form another component of this research project.

Traffic and service characteristics

27. Traffic and service characteristics of each lock are available in the Corps' Performance Monitoring System (PMS). The PMS, maintained by the Institute for Water Resources (Fort Belvoir, Va), is part of the Inland Navigation System Analysis (INSA) program and involves collecting, editing, maintaining, and analyzing data from all Corps-owned and -operated locks.

28. These data have been collected since March 1975 and contain descriptions of lock physical dimensions, traffic, and service time statistics. Quarterly summaries are produced for each lock. These summaries are in the form of three tables, illustrated by the examples shown in Tables 5 through 7. Although the dimensional data in Table 5 are already available (with other information) in the WES data base, the traffic and service time statistics in Tables 6 and 7 are unique and will be extremely useful in estimating both the degree of use of each facility and the consequences of facility performance as affected by REMR actions.

Research Issues and Approach

29. A number of fundamental issues need to be addressed in developing a management system for evaluating, maintaining, repairing, and rehabilitating civil works:

a. REMR activities need to be seen in their economic, as well as technical, dimensions. Although the REMR program certainly a

Table 5

PMS Data on Physical Dimensions of Locks

EROC	District Name	Division Name	Dimensions
B2	New Orleans	Lower Miss Valley	

RIVER	LCODE-LOCK NAME	LEN/WID/DRAFT (FT/FT/FT)
GULF INTRACOASTAL	01-PORT ALLEN LOCK	1202/0084/15.0
	02-BAYOU SORREL LOCK	0800/0056/16.0
	03-INNER HRBR NAVIGATION CANL LK	0626/0074/40.0
	04-ALGIERS LOCK	0760/0075/15.0
	05-HARVEY LOCK	0426/0075/14.0
	06-BAYOU BOEUF LOCK	1148/0075/15.0
	07-VERMILLION LOCK	1195/0056/14.0
	08-CALCASIEU LOCK	1194/0075/15.0
ATCHAFALAYA RIVER	11-BERWICK LOCK	0300/0045/11.0
GULF INTRACOASTAL	21-SCHOONER BAYOU CONTROL STRUCT	9999/0075/14.0
	22-CATFISH POINT CONTROL STRUCT	9999/0056/16.0
	23-CALCASIEU SALT WATER BARRIER	9999/0056/15.0
BAYOU TECHE	31-KEYSTONE LOCK	0160/0036/12.0
FRESHWATER BAYOU	41-FRESHWATER BAYOU LOCK	0590/0084/15.0
OLD RIVER	51-OLD RIVER LOCK	1200/0075/15.0

Table 6

PMS Data on Lock Traffic

EROC	DISTRICT NAME	DIVISION NAME
83	ST. LOUIS	LOWER MISS VALLEY

RIVER/LOCK NAME	TOWS	VESSEL			BARGES			LOCKAGES				TONNAGE
		RECRTN	OTHER	TOTAL	EMPTY	FULL	TOTAL	COMMER	RECRTN	OTHER	TOTAL	(KTONS)
KASKASKIA RIVER												
KASKASKIA RIVER NAVGTN LK												
UPBOUND STATISTICS	132	41	63	236	475	1	476	195	29	0	224	0
DOWNBOUND STATISTICS	128	40	70	238	0	472	472	200	30	0	230	706
TOTALS	260	81	133	474	475	473	948	395	59	0	454	706
MISSISSIPPI RIVER												
LOCK & DAM 24												
UPBOUND STATISTICS	243	4	21	268	2334	343	2677	418	4	8	430	538
DOWNBOUND STATISTICS	182	5	10	197	69	1377	1446	285	4	5	294	1958
TOTALS	425	9	31	465	2403	1720	4123	703	8	13	724	2496
LOCK & DAM 25												
UPBOUND STATISTICS	240	6	45	291	2350	355	2705	441	6	6	453	563
DOWNBOUND STATISTICS	171	9	40	220	7	1394	1464	280	6	4	290	1986
TOTALS	411	15	85	511	2420	1749	4169	721	12	10	743	2549
LOCK & DAM 26												
UPBOUND STATISTICS	631	2	9	642	6205	1399	7604	1129	1	3	1133	2282
DOWNBOUND STATISTICS	662	0	11	673	420	6961	7381	1166	0	6	1172	10107
TOTALS	1293	2	20	1315	6625	8360	14985	2295	1	9	2305	12389
LOCK & DAM 26 AUX I												
UPBOUND STATISTICS	268	2	78	348	704	262	966	517	1	12	530	462
DOWNBOUND STATISTICS	230	5	85	320	195	668	863	484	3	7	494	1040
TOTALS	498	7	163	668	899	930	1829	1001	4	19	1024	1502
CHAIN OF ROCKS LOCK & DAM 27												
UPBOUND STATISTICS	913	7	106	1026	7281	1691	8972	934	2	7	943	2913
DOWNBOUND STATISTICS	901	3	90	994	578	8021	8599	933	0	10	943	11804
TOTALS	1814	10	196	2020	7859	9712	17571	1867	2	17	1886	14717

Table 7

PMS Data on Lock Service Characteristics

EROC	DISTRICT NAME	DIVISION NAME
83	ST. LOUIS	LOWER MISS VALLEY

	LOCK PROCESSING TIME (MIN.)												DELAYED	DELAY	DELAY	DELAY
	APPROACH			ENTRY			CHAMBER			EXIT			VESSELS	TIME	AVG	MAX
	MIN	AVG	MAX	MIN	AVG	MAX	MIN	AVG	MAX	MIN	AVG	MAX		(IN MINUTES)		
KASKASKIA RIVER																
KASKASKIA RIVER NAVGTN LK	1	6	28	1	4	21	5	8	20	1	4	15	13	344	26.5	40
MISSISSIPPI RIVER																
LOCK & DAM 24	1	12	430	1	9	142	5	8	67	1	16	240	172	14628	85.0	776
LOCK & DAM 25	1	9	89	1	8	87	3	7	39	1	13	70	459	21164	46.1	725
LOCK & DAM 26	1	5	109	1	9	160	4	11	82	1	12	155	1305	681941	522.6	4875
LOCK & DAM 26 AUX 1	1	7	169	1	7	243	4	11	188	1	11	106	647	130801	202.2	3468
CHAIN OF ROCKS LOCK & DAM 27	1	10	49	1	7	30	3	11	45	1	7	31	1374	72237	52.6	505
CHAIN OF ROCKS LOCK & DAM 27 AUX	1	7	48	1	3	43	5	10	34	1	3	39	285	6141	21.5	203

addresses important technological questions in the maintenance of existing structures, it is also an increasingly important component of the Corps' mission to provide efficient, reliable, and safe waterborne transport. The consequences of REMR policy alternatives (to the Army, shippers, and barge operators) must be reduced to an economic basis for comparison.

b. There are trade-offs among evaluation, maintenance, repair, and rehabilitation over time that need to be accounted for. In analyzing these trade-offs, one must weigh the value of an activity against the cost of performing it, the degree to which one type of activity may substitute for another, the benefits versus the penalties of deferring an activity, and interactions among activities (e.g., whether it makes sense to schedule one activity to coincide with the performance of another).

c. There are also trade-offs in distributing or allocating resources among competing needs throughout a network of facilities. This problem, taken in concert with item b, defines a capital budgeting problem for REMR that is complicated to solve in the general case.

_d_. Beyond the need for economic relationships in item _a_, there are distributional questions (e.g., to whom do the costs and benefits of the REMR program accrue?), and the influence of noneconomic decision criteria (e.g., defense needs) on selection of the most appropriate REMR alternatives.

_e_. The design of the management system must consider the methodology most appropriate to the Corps' needs, and what analytic models are available to meet those needs. These questions relate, for example, to the prediction of future consequences of different REMR policies, the optimization of REMR policies, and the provision of appropriate information to help explain and interpret predictions and results and defend and justify particular policies or courses of action.

_f_. Related to item _e_ are the uses to which the management system will be put, identification of the potential users of the system, and for what level of management should results be designed. The structure and format of reports are particularly important: e.g., the level of aggregation or detail provided, the types of information displayed, the types of comparisons or analyses conducted, and the degree of explanation (backup reports) provided.

30. These issues are fundamental to the concept of the proposed management system. Although the work to date has begun to deal with them, they will remain as active concerns throughout system design, programming, and implementation. This report documents the first steps in this process of management system development in response to the several issues above. In Part II the general structure and analytic approach of a facility management system will be formulated, relying heavily on concepts of life-cycle costing and illustrating how they may be used to address some of the concerns above. Parts III and IV will review data and predictive models now available in two key areas, respectively: (a) prediction of REMR requirements and costs and (b) prediction of the consequences of REMR actions. Part V applies these general relationships to propose specific models used in a prototype of the REMR Management System. It then describes the application of the computerized prototype to example problems, and the interpretation of results. Part VI concludes the report.

PART II: CONCEPTS UNDERLYING A FACILITY MANAGEMENT SYSTEM

Rationale for Life-Cycle Costing

Analysis of REMR alternatives

31. The Corps of Engineers has extensive experience applying economic principles to engineering decisions. Calculations of benefits versus costs have been routinely applied to the evaluation of water projects for many years. These procedures extend projections of project costs and benefits through an analysis period and, by comparing the discounted totals of various alternatives, can identify the economically most efficient project option or decision.

32. As applied to the analysis of REMR projects, life-cycle costing of existing facilities would consider the total service life costs of evaluation, maintenance, repair, rehabilitation, reconstruction, operation, use, and (in special cases) abandonment of a facility as they relate to REMR policy. By introducing both economic and technical information, life-cycle costing is particularly well suited to the analysis of REMR alternatives (with locks as an initial example) as discussed in the following paragraphs.

33. First, as a very visible and vital component of the inland waterways, locks embody critical trade-offs among the economic costs of facility design and construction, inspection, maintenance, operation, repair, rehabilitation, and reconstruction (all borne by the Corps), and of vehicle operation, travel time, travel reliability, safety, and other costs perceived by shippers and barge operators. Since these costs accrue in a stream extending typically over several decades, life-cycle costing is a natural and appropriate methodology for analyzing REMR options.

34. Second, for those components of locks that wear or deteriorate gradually, but do not fail catastrophically, it is not immediately apparent at what point repair or renewal should be done. This complicates the specification of REMR standards governing facility performance, safety, and cost and also complicates the interpretation of performance data. Life-cycle cost analyses can be used, however, to estimate both the total and the marginal benefits and costs of alternative standards, thereby providing economic as well as engineering guidance on the selection of the appropriate REMR strategy.

35. Third, life-cycle cost analyses can, if properly formulated, help to understand how REMR activities influence facility performance. This capability contrasts with conventional design practice, for example, which considers the effects of the operating environment, traffic usage, structural and material properties, foundation geology, and time-dependent changes in facility characteristics, but which offers no information relating REMR policy to the subsequent rate of facility deterioration. Where this gap in information exists, policy makers cannot accurately analyze the impacts of deferred maintenance, nor can they effectively assess the potential trade-offs among initial design standards, construction quality, and future REMR requirements. Such studies are feasible, however, using life-cycle analyses.

36. Fourth, decisions to repair or renew civil works are complicated by the wide range of possible activities, ranging from minor routine maintenance to major rehabilitation or reconstruction, and the various frequencies and intensities of inspection. Life-cycle analyses can illuminate the long-term costs and benefits of these different courses of action.

Demand-responsive approach

37. The implementation of life-cycle analyses of facilities required a new approach to looking at facility performance and the factors that influence costs throughout its service life. This approach is referred to as "demand responsive," in that maintenance, rehabilitation, and reconstruction are viewed as responses to the demand for repair or renewal of the facility. This demand for work arises through both a physical dimension (the condition of the facility, reflecting the quality of initial design and construction, the accumulation of wear and damage from the combined effects of traffic loads, environment, and age, and corrections due to past repairs), and a policy dimension (standards of initial design and construction, and the level of maintenance, repair, rehabilitation, or reconstruction to be performed, expressed through quality standards). Furthermore, since the prediction of facility condition is central to the demand-responsive approach, one can compute the impacts, as well as the costs, of alternative investment policies.

38. Treating REMR actions as demand-responsive activities requires that three additional elements be introduced within existing planning and management models. The first is that estimates of future resource requirements and costs cannot be extrapolated from past trends, but rather must be based upon

predictions of structural and operational deficiencies caused by use, environment, and age. The second is that in designing models to be sensitive to the implications of different policies, there may be unambiguous statements of REMR policies themselves, defining the types of preventive or corrective actions to be taken, and when and where they are to commence. The third is that new relationships must be identified between the as-maintained state of the civil facility, and the impacts to both the Corps and the users of the facility, providing a measure of the benefits (or disbenefits) of each policy at the costs computed above. Organization of these ideas within a unified structure is shown in Figure 9.

Applications

39. The analytical procedures needed to implement the management structure in Figure 9 have been organized within simulation models and closed-form optimization procedures, both of which have been used to address different types of investment decisions in the transportation field. The development of simulation models is described by Markow and Brademeyer (1981) and Markow et al. (1984), while the mathematical optimization procedures are presented in Fernandez-Larranaga (1979). These tools have been applied to a diverse set of problems, encompassing optimization of investments (Markow 1982a, Friesz and Fernandez 1979, Fernandez and Friesz 1981), evaluation of alternative investment programs (Markow et al. 1982, Markow 1984), allocation of scare resources among competing activities (Markow 1978), predicting impacts of deferred maintenance (Markow 1982b), and financing maintenance and rehabilitation (Markow and Wong 1983, US Department of Transportation 1983). Recently the optimization approach in Fernandez-Larranaga (1979) was refined to develop simplified models and engineering curves for use by engineers in the field (Balta 1984). Work is now proceeding, in parallel with this project, to adapt optimization approaches to management systems. Thus, the demand-responsive approach provides a very powerful framework for addressing decisions in facility life-cycle management and can be applied to a number of problems in facility investment.

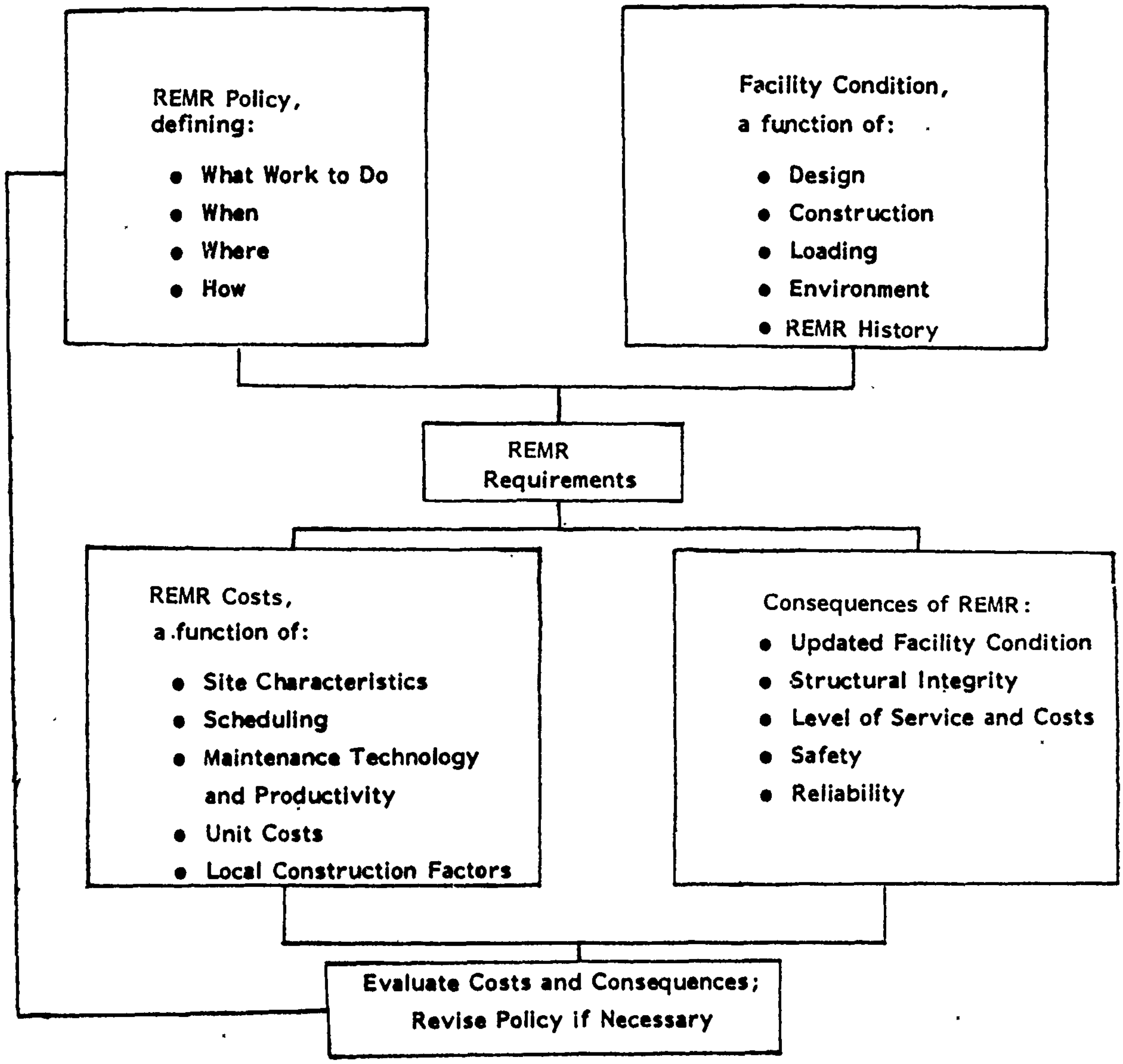


Figure 9. Approach to REMR planning and management

Analyzing Life-Cycle Cost Streams

Examples of typical streams for facilities

40. Agency and user cost streams are shown schematically in Figure 10 for two facility strategies. It is assumed that traffic and environmental factors are identical in both cases, but that initial facility design and subsequent performance differ in response to capital investment and maintenance policy.

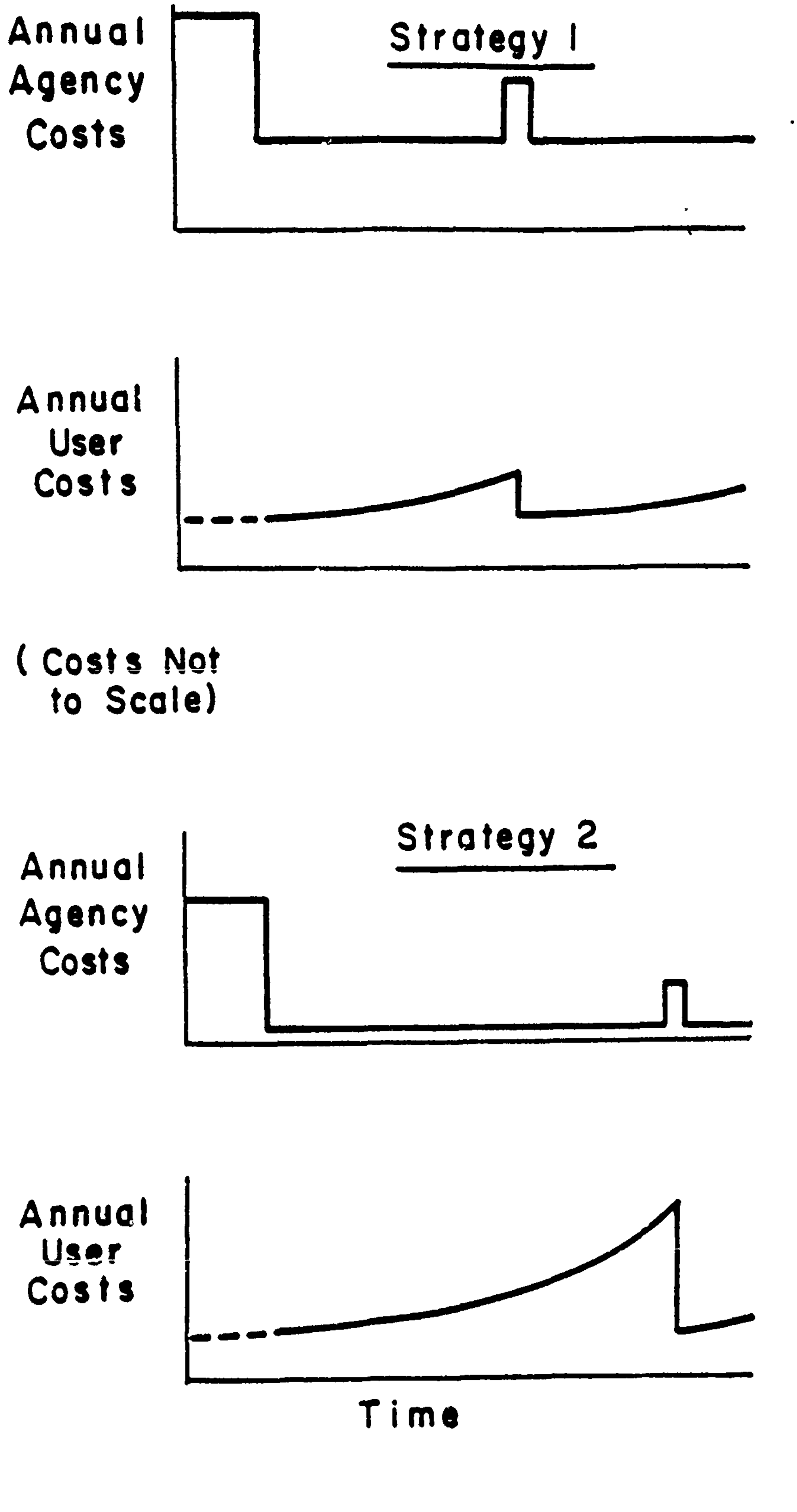


Figure 10. Schematic cost streams for two REMR policies

41. These differences are evident in the respective cost streams. Strategy 1 in Figure 10 entails higher agency costs for construction, maintenance, and rehabilitation, but lower costs of facility usage. Strategy 2 presents the opposite pattern; lower agency costs, but higher user costs. The first strategy may be interpreted, for example, as that of a facility built and maintained to very high standards, to ensure premium service throughout its life. The second strategy may then be interpreted as a conventional facility maintained adequately but not exceptionally.

42. From an agency perspective, strategy 2 is the lower cost alternative and perhaps would be preferred. From a total cost viewpoint, however, the savings in agency costs by moving from strategy 1 to strategy 2 are offset by the increase in user costs. Therefore, one cannot say *a priori* that one strategy is better than another; that determination depends upon the relative total costs of the two options, and the discount rate at which they are analyzed.

43. To analyze the total costs, each of the cost streams in Figure 10 would be discounted to compute present costs. Present agency costs and present user costs would be summed in each strategy to yield net present total costs. Respective net present total costs would then be compared to identify the alternative having the lowest total discounted costs; that alternative is then the preferred option of the two. The following sections develop in more detail the types of models needed to produce these life-cycle cost estimates.

<u>Simulation of facility performance, costs, and impacts</u>

44. The simulation of facility performance is based upon deterioration functions illustrated in Figure 11. Although deterioration is shown as a function of time (for simplicity), the changes in facility condition are actually due to a complex interaction among several factors. To support the technical computations required, data on structural and materials properties, current condition, traffic usage, and environmental factors, as well as REMR policy, must be provided at the start of the analysis period for each lock in the network. Thereafter, the results of the simulation of each year's performance define the conditions at the start of the subsequent year's simulation.

45. Each REMR policy to be considered is tested by the model, which simulates the performance of the civil works, computes maintenance and rehabilitation costs, and predicts how the policy will impact upon preserving

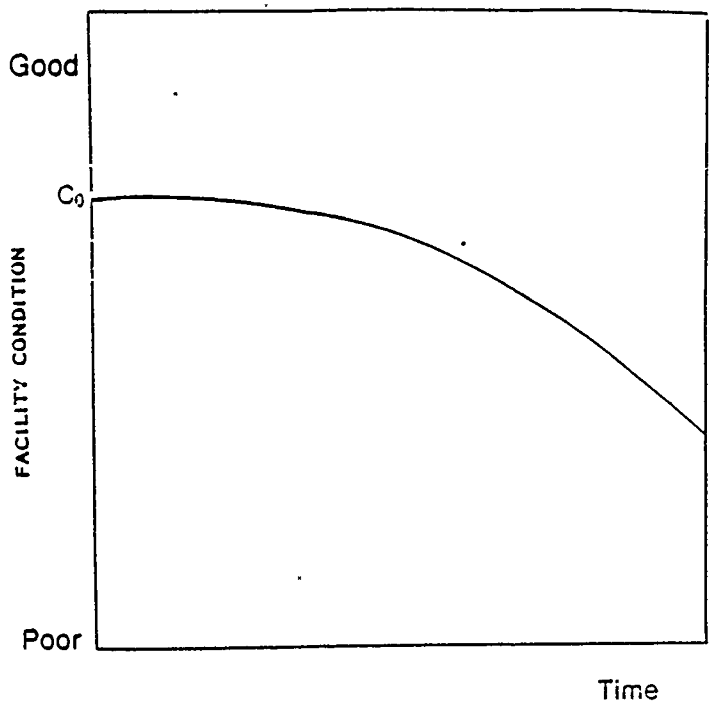


Figure 11. Example facility deterioration

the investment and waterway operations through some analysis period. This process is then repeated for several policy options, to compare relative costs and impacts, to identify any additional policies that should be investigated, and to decide upon a single policy that forms the basis for programming and budgeting future activities.

Major versus minor REMR activities

46. It is easy to visualize the effects of major maintenance or repairs, rehabilitation, or reconstruction upon the condition of the facility. These activities produce a substantial, immediately identifiable correction of deficiencies, represented by abrupt improvements in the condition curve, as shown in Figure 12. The effects of routine maintenance, facility inspection and evaluation, and minor repairs, on the other hand, are harder to detect. Improvements in facility condition may be so small as to escape measurement, or the maintenance activity may not correct any existing damage, but rather may prevent future damage, or may slow the current rate of deterioration. Inspection and evaluation also serve to some extent as preventive activities, helping to identify and locate impending distress before it becomes a major problem.

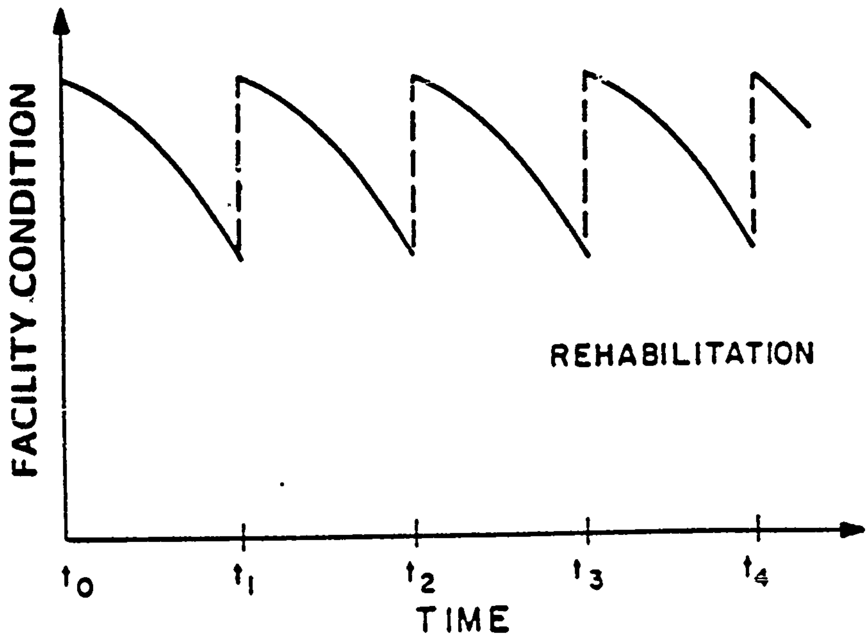


Figure 12. Analytical representation of rehabilitation

47. Therefore, it is reasonable (at least at a systemwide level) to account for major repairs by measurable changes in the current condition of the facility (as denoted by the jogs in the curve in Figure 12), and to represent routine maintenance, inspection, and evaluation in different ways.

48. One representation of these "minor"* activities is as an adjustment in the slope of the deterioration curve as shown in Figure 13. Not only does this approach approximate the effects of the routine activities discussed above, but it also provides a way to reflect current facility condition as dependent upon past maintenance performed.

49. A second way to represent routine evaluation, repair, and maintenance is to consider the future facility condition as subject to uncertainty--in essence, to attribute some reliability to the facility. Reliability in this context would be defined as the probability that the future condition is equal to or exceeds some value. This reliability could then be related to the level

---

* Routine maintenance, inspection, and evaluation are "minor" only in the sense that they are intended to prevent incipient distress from reaching major proportions and are therefore limited in scope and relatively low in cost. The potential benefits of these activities, however, can be substantial.

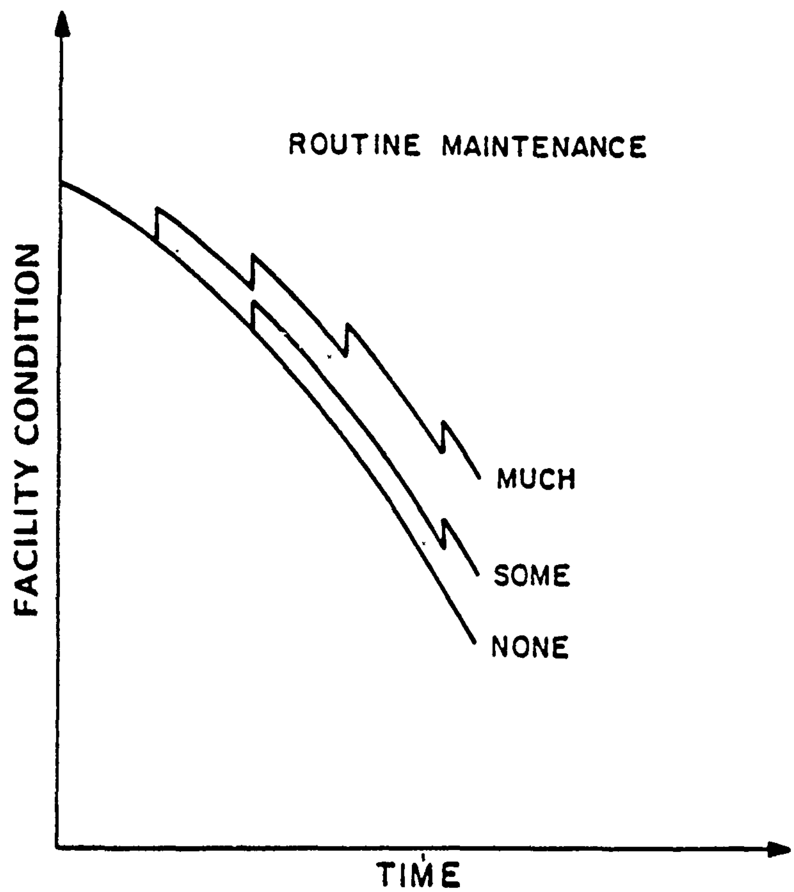


Figure 13. Analytical representation of routine maintenance through changes in slope of the deterioration function

of routine maintenance, inspection, and repair that is assumed will be performed between now and the selected future time.

50. Figure 14 illustrates this concept for two hypothetical routine maintenance policies. Maintenance is used as an example; other minor, routine REMR activities could be similarly illustrated. The reliability distributions for the two cases are indicated at time T. These distributions are actually dependent upon several factors besides the assumed maintenance policy: e.g., the quality of initial construction, the uncertainty in current facility condition (i.e., the reliability of current methods of inspection, detection, and evaluation), and uncertainties in predicting future traffic use, environmental conditions, and other factors affecting deterioration. However,

Figure 14 illustrates only the dependence of these distributions upon routine REMR activities.

51. The distribution in the upper graph in Figure 14 is based upon better levels of maintenance presumed to be applied through time T, while the distribution in the lower graph derives from a less frequent, or lower quality maintenance. The two cases have been constructed so that the means of the distributions at time T are the same; therefore, the deterioration curve follows the same path in both examples in Figure 14. The effect of the maintenance policies is seen rather in the variances or standard deviations of the respective distributions, with the lesser maintenance policy presumed to result in a higher standard deviation. Essentially this means that less maintenance or less inspection, evaluation, and routine repair of a facility leads to a loss in the reliability of its future condition.

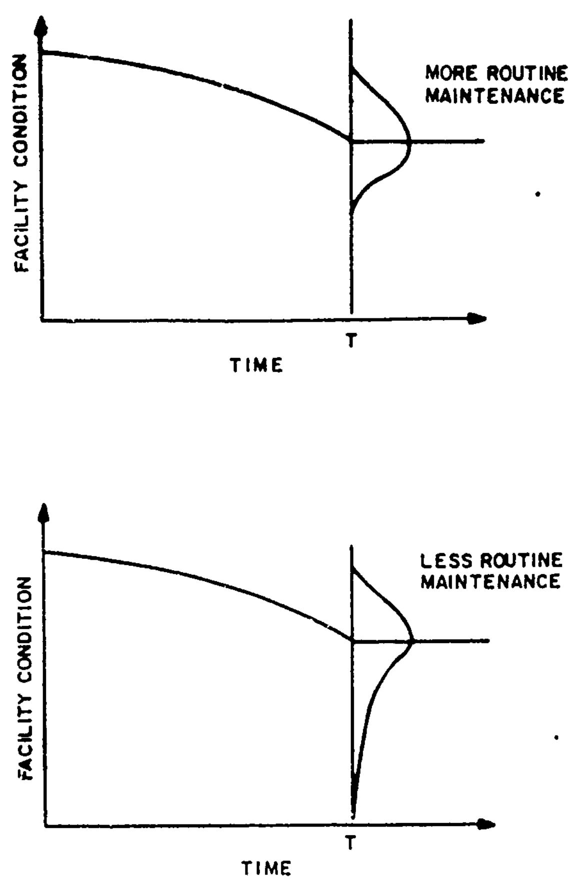


Figure 14. Analytical representation of routine maintenance through changes in reliability of facility condition

52. Effect of REMR activities and technology. The prediction of facility performance for two different policies of routine maintenance and rehabilitation is shown in Figure 15. (It takes two separate simulations using a deterioration model to generate these results.) Note that for Policy 1, both the quality standard Q, and the quality of routine maintenance (denoted by the Maintenance Quality Index, or MQI) are higher than for Policy 2. As a result, the average system condition is also higher for Policy 1. Predictions of system performance (i.e., histories of facility condition) are accomplished using deterioration functions and specifications of REMR policy discussed earlier. Whereas Figure 15 shows two policies as examples, in fact several policies may be simulated for comparison. Observe also that the degree to which REMR actions correct or prevent distress depends both upon the condition of the facility when the action is performed and the technology represented by that action. In this way, the benefits of new technological developments in REMR can be assessed. Although Figure 15 shows the effect of routine REMR activities as changes in the slopes of the deterioration curve, an analogous figure using the reliability concept in Figure 14 could also be constructed.

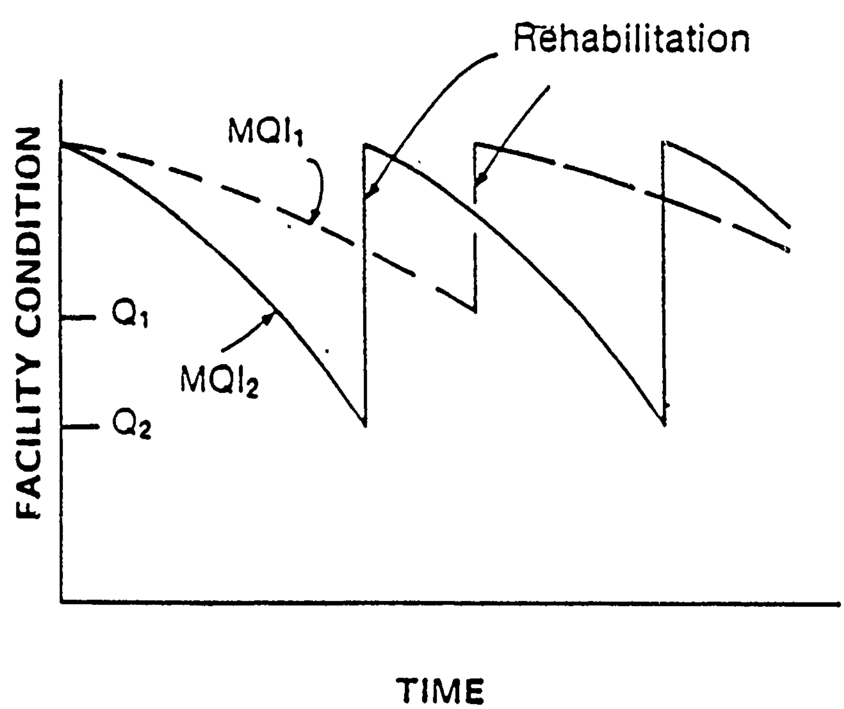


Figure 15. Examples of facility condition for two maintenance and rehabilitation policies

53. Costs. Costs for each policy are tabulated based upon the damage repaired, the maintenance or rehabilitation technology employed, and unit costs of labor, equipment, and materials. The resulting cost histories for the two policies in Figure 15 are shown schematically in Figure 16. Routine maintenance is costed on an annual basis, with the better policy costing slightly more. Major repairs are represented by spikes in the cost history. Under an inferior rehabilitation policy, both the magnitude of costs and the time intervals between successive performance of an activity may differ from those of better policies. It is assumed that all REMR activities are performed efficiently; in this case, better policies would indeed cost more. Also, Figure 16 shows the idealized case. Annual costs of routine maintenance are not necessarily uniform, although it is simpler to think of them that way.

54. The consequences of REMR policy associated with the condition histories in Figure 15 are shown in Figure 17. For simplicity, a general benefits measure is shown. Several such functions could be developed, for travel time and reliability, safety, energy savings, etc. The important thing to note is that the impact bears a direct relationship to the as-maintained condition of the facility and is therefore sensitive to change in REMR policy.

55. Evaluation of results. Results of the simulation in Figures 15 through 17 can be compared to identify the best policy, with or without budget constraints. To illustrate how this is done, assume that the benefits in Figure 17 can be reduced to monetary terms and thus compared directly to costs. Furthermore, assume that rather than investigating only two policies, several policies were tested using a simulation model.

56. The results of each policy can be organized in terms of ascending costs to the agency owning the facility. Since impacts or consequences of REMR policy are in monetary terms, they can be plotted on the same graph with costs for each policy. If REMR policies are sensibly defined, policies that are more expensive to the agency should yield more advantageous impacts (i.e., greater reductions in safety, travel time, or trip reliability costs), leading to the diagram in Figure 18.

57. Identification of the most advantageous policy now becomes a question of minimizing total transport-related costs for the network configuration and traffic specified. In the absence of budget constraints, the appropriate

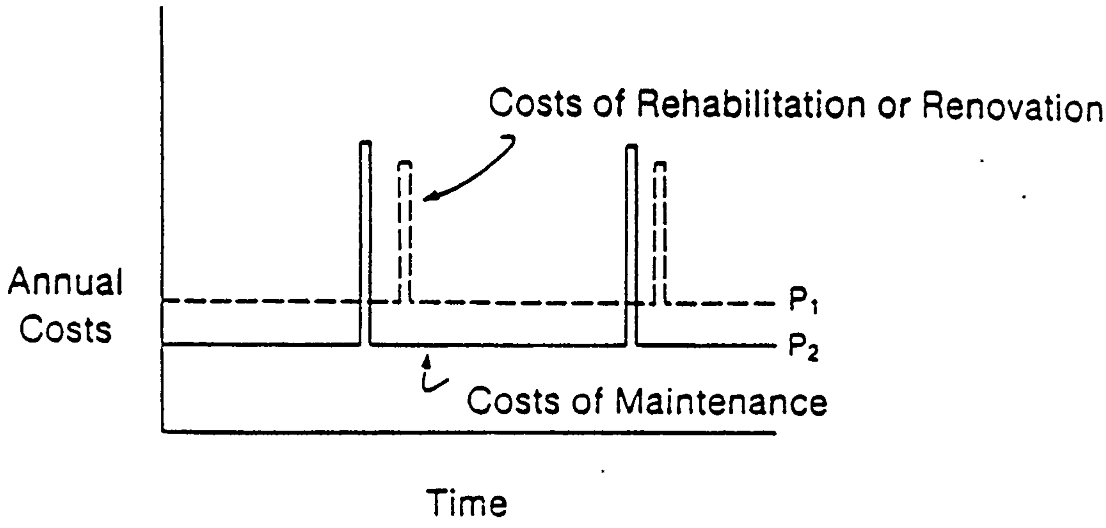


Figure 16. Annual costs for two REMR policies illustrated in Figure 15

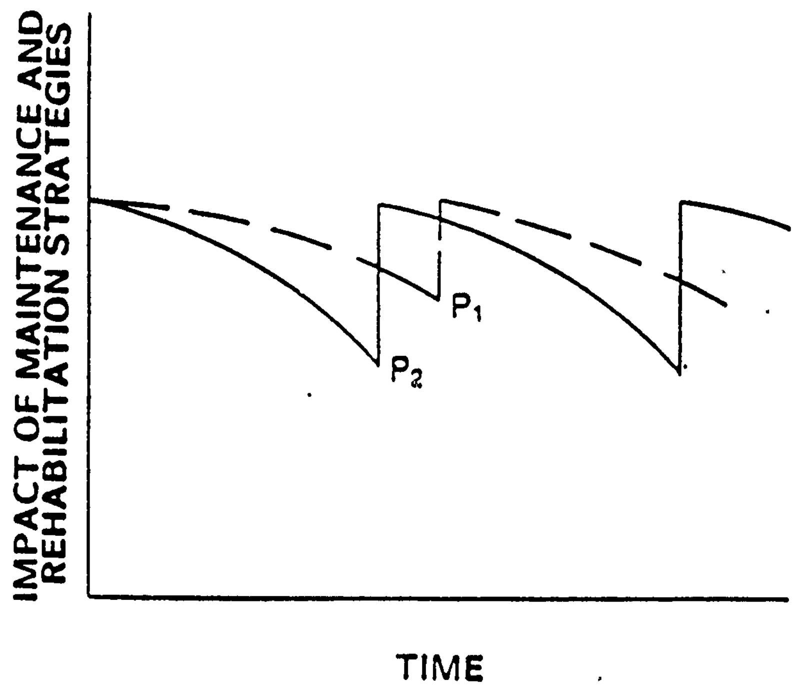


Figure 17. Impacts of the two REMR policies illustrated in Figure 15

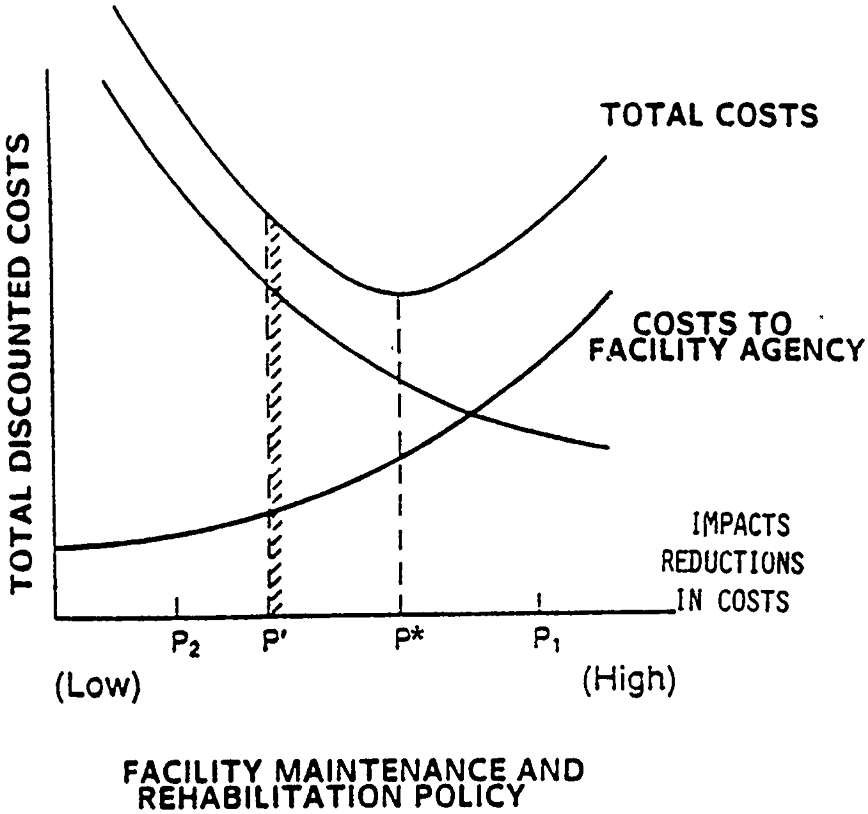


Figure 18. Example determination of the optimal REMR policy

policy is shown in Figure 18 as P*, since total costs (REMR costs to the agency, plus costs associated with impacts of REMR activities) are minimized at this point. If a budget constraint is imposed, the best policy that can be funded lies to the left of P*, e.g., at P'.

Optimization procedures

58. The engineering and economic relationships of the example in Figures 15 through 18 may also be formulated as mathematical optimization problems. The solutions to these problems lead directly to the optimal level of routine activities (i.e., the most efficient MQI in Figure 15), or the optimal timing of major projects (i.e., the points in Figure 15 at which the facility condition is renewed). Although the technical relationships used in optimization are typically not as sophisticated as those in simulation models, they are able to capture the essential trends driving a solution and thereby provide a

higher degree of management insight. Optimization approaches employing control theory to capture elements of the demand-responsive approach discussed earlier have recently been applied to both routine maintenance and rehabilitation (Balta 1984). The application of optimization principles to REMR policy analysis is a potential topic for future research in this project.

PART III: PREDICTING REMR REQUIREMENTS AND COSTS FOR LOCKS

Analytic Requirements

59. The prediction of REMR requirements and costs according to the life-cycle framework developed in Part II is based upon the following analytic models and data:

a. Definition of measures of condition of the facility.

b. Models to predict the deterioration in this condition over time, as functions of initial design and construction standards, facility age, traffic use, operating environment, and other causal factors.

c. Statements of REMR policy, expressed as quality standards defining what work is to take place, when, and where.

d. Sets of REMR activities, defining the technology to be used to correct or prevent deterioration, and the amount or quality of the improvement to be gained.

e. Models to predict the costs of these REMR alternatives.

60. These analytic components, when assembled within a consistent management approach, may be used to assess future REMR needs (items a, b, and c), responses (item d), and costs (item e). For civil works such as locks, the development of these models requires research and analysis of both theoretical principles and empirical data. The problems that must be dealt with are as follows:

a. There is no generally accepted method of measuring and recording facility condition. This issue encompasses a number of subsidiary concerns, such as the appropriate index to be used to measure condition, the measurement technology, frequency, and reliability, the level of detail or aggregation that the measurement represents, and the interpretation of such measurements.

b. The relationship between REMR activities and facility performance is not well documented and understood, as discussed in Part II. This is not simply a question of lack of particular data, but more fundamentally entails the following:

(1) Formally understanding how maintenance, evaluation, repair or rehabilitation may affect current condition and future performance.

(2) Designing theoretical and empirical methods to confirm the mechanisms involved.

(3) Documenting specific results of different REMR policies. To date these issues are not well addressed analytically

for any civil facility, and are the subject of research for several types of transportation structures.

c. Data are not easily assembled for relevant aspects of current REMR programs within the Corps' inland waterways network. Much of the information on facility condition, REMR performance, and cost histories are housed at the District level and may not be consistent from one District to another.

61. As a result, the information in this part represents suggested or example approaches rather than formal models. Measurement of facility condition and prediction of REMR requirements and costs are discussed below in terms of general approach, available data, and proposed models. The prediction of REMR requirements and costs will require additional research before a management system conforming to the principles in Part II can be implemented. The research must include a thorough review of potential models in terms of their formulation, estimation, and verification.

Facility Condition

General concepts

62. Indices to measure facility condition fall into one of three general classifications:

a. Quantification of amounts of damage or distress that have accumulated within the facility. These indices may be the aggregation of different categories of distress related to the origins and mechanisms of damage (e.g., fracture, corrosion, wear, permanent deformation, and materials disintegration).

b. Results of nondestructive tests (e.g., dynamic loading tests of bearing structures, deflections or distortions measured by conventional surveys or by new techniques such as lasers, or cross-sectional thicknesses as measured by sonic or other means).

c. Indices relating some aspect of the physical condition of a facility to its operational characteristics or serviceability (where serviceability is defined as the degree to which a facility fulfills its intended level of service to users). An example for locks would be the service rate (tows per hour) as a measure of current condition.

63. Each of these types of indices has a particular use. For example, measures of damage (item a) or results of nondestructive tests (item b) are useful in determining the need for REMR work, since the amount of distress can be directly related to the corrective work required, and the current physical

condition can be used to evaluate current status and to assess if any hidden damage exists or preventive work is needed. In the ideal case, one would like both to relate one type of index to another and to derive prediction models of changes in these conditions over time.*

64. Such indices have not yet been established for civil works under the jurisdiction of the Corps of Engineers and are the subject of current research sponsored by the REMR program. Two reports have already been issued on sheet piles and miter gates (Mlaker 1984, Mlaker 1985), and work for these structural components is continuing at Iowa State University and Massachusetts Institute of Technology (MIT) (User's Manual 1986, Shrestinian 1985, Lovesky 1986). Beyond these efforts, however, much more basic consideration must be given to what kinds of condition indices would be useful in a management system for REMR activities.

65. First, indices developed for a management system should describe the system of facilities as completely as possible and to an appropriate level of aggregation and detail. These indices must be able to capture changes in condition that affect structural or operating performance or the requirements for REMR activities. Since the Corps' inventory of civil works extends to many types of structures, indices must ultimately be developed for all types, not just for locks on inland waterways. With respect to current research, a decision must be made on how the detailed information now being developed for the condition and behavior of sheet pile walls and steel gates individually is to be included within a measure of overall lock condition that encompasses concrete walls and mechanical equipment as well. This can be done by dealing with a vector of indices for key elements or components of the facility (e.g., gates, walls, mechanical equipment of locks) or by combining these individual indices within a single composite index for the facility as a whole. The reason for doing this, of course, is that the impacts of REMR activities as

* Considerable work on condition indices has been done with respect to highway pavement and railroad track. For example, highway engineers are able to relate an index of pavement serviceability to the type and extent of surface damage present. Furthermore, models have been developed to predict changes in this serviceability index as functions of pavement structural and materials properties, traffic, weather, and subgrade soil. Similarly, indices and models of track condition have been researched. What is needed is to apply concepts of this type to components of the waterways network.

seen by shippers and barge operators depend upon the efficiency and integrity of the lock as a whole, not upon its components individually.

66. Second, the selected condition indices must be able to be measured or quantified in some practical way. The technology of measurement should be specified, or perhaps new technology developed (particularly for those conditions that are not visible or not easily measured). The allowable tolerance of the measurement (i.e., precision required) and the reliability of the technology (i.e., accuracy of the reading) should be established. The specified frequencies of measurement must be related to the cost and these costs must be weighed against the needs for updated data within the management system.

67. Third, the indices must be relevant to the objectives of the management system; they must convey information useful to the prediction of REMR requirements, costs, and the impacts of facility condition. For example, consider some measurement of cracking in a structure. That measurement must be able to be related to the reliability of the structure (i.e., the likelihood that it will perform without failing through some future time) and to the amount of REMR work required to remedy the condition if need be. Thus, the meaning of the index should be clear (i.e., whether surface or subsurface cracks are included, whether all cracks, or just those exceeding a certain length or width, are included, the standards by which the degree or severity of cracking are expressed, etc.). Guidelines on the determination of index values need to be established to ensure uniformity among Districts and Divisions and to allow cross-sectional and time-series comparisons of facility performance.

68. Finally, the indices should portray to the greatest extent possible a one-to-one relationship between the index value and the facility condition itself that is represented. Ideally, each value of the condition index would uniquely reflect one and only one possible state of the facility or component and would even convey some information about how and why the facility arrived at such a state (i.e., what deterioration mechanisms have been active). In practice, this ideal is difficult to achieve since many degrading and corrosive processes occur simultaneously in complex structures. Therefore, this criterion is viewed more as a desirable objective rather than a hard and fast rule.

69. Given the infancy of research in this area, condition indices for Corps facilities have not yet been determined. The following section discusses some of the data available in field offices that may be used to begin the process of index definition and calibration. As a result of current and future research, new measurement standards, procedures, and technologies may be brought to bear in determining the changes in facility condition over time. Proposed measures are described to illustrate the use of indices in predicting maintenance costs and requirements, and consequences of maintenance or rehabilitation.

Data on facility condition

70. Annual condition surveys. The annual condition surveys are at the heart of the process to assess facility condition. These reports, produced by the lockmaster and his staff, describe the performance of the lock and machinery, maintenance done, repairs made, and incipient problems that are watched. Results of divers' biannual inspections contain detailed information, usually regarding both good and bad conditions, about the underwater features of the gates, valves, and chambers.

71. An annual survey (dated 1 February 1984) from the Montgomery Locks and Dam on the Ohio River was reviewed. It assesses the condition of the Montgomery facility for 1983. The condition survey for Dashields Locks and Dam, also on the Ohio River, was also reviewed.

72. Both reports emphasize the most urgent repair needs. However, since Montgomery underwent major rehabilitation in 1984 and Dashields in 1986, these surveys were conducted just before major rehabilitation of facilities in relatively poor condition.

73. Twenty-three lock and dam facilities produce twenty-three different Annual Condition Survey Reports. Every year, the engineers at the District office must read twenty-three reports ranging in length from 5 to 50 pages and differing in presentation format. No uniformity exists in what gets reported and what gets left out, nor does a system exist to characterize the condition (e.g., whether "good" versus "fair" or "poor"). In lieu of such a characterization, planners appear to exercise judgment based on actual condition as determined from personal knowledge and direct communications with the site, histories of expenditures, and past reports to determine which projects get funded and at what priority.

74. Periodic inspections. Periodic inspections of locks now occur in roughly 5-year intervals unless conditions at a particular facility require close monitoring. Based on field interviews at the Pittsburgh District offices in January 1986, the inspection team typically reviews recent repair work and recent problems from previous reports and inspects the site for safety problems.

75. Typically, the inspection team consists of about a dozen members, including mechanical engineers, an electrical engineer, and civil engineers in both the geotechnical and structural areas. Often, one to three engineers or administrators from the Division office participate in the inspection, as does the area manager and two or three lock personnel. Divers' inspections usually are included, particularly where a condition calls for monitoring. Each inspection takes about 2 days, not including a day for briefing and review of earlier reports before the inspection, and the time required for each member to submit his/her reports and recommendations.

76. Periodic inspection reports differ from annual condition surveys in a number of ways. Most notably, they are larger and more comprehensive. The periodic inspection report may include a synopsis of the history of major repairs, photographs, and facility plans and drawings if they have not appeared in a recent report. The 5-year report also presents documentation on the instrument readings at a facility. These include survey results of alignment and settlement, piezometer readings, soundings, weir readings, and if necessary, crack measurements. Accompanying the written results of the readings are the data plots and drawings appropriate for each instrument.

77. Despite the higher level of technical discourse, the periodic inspection typically does not, nor is it intended to, discover problems not realized by the site crew. The documentation gives analytic muscle to the annual condition survey reports and serves as a second-level check on work carried out by the site crew and independent contractors. These inspections are used to support the site staff's recommendations of needed work.

Proposed measures

78. Research to develop condition indices as performance measures is proceeding concurrently with this research. Therefore, this section shows how such measures may be used to reflect the facility performance at a level of aggregation consistent with the objectives of a REMR Management System. It is

assumed that the measures characterize facility performance adequately and can be obtained through currently available technology for inspection and monitoring.

79. Furthermore, future facility condition is subject to uncertainty due to imperfect knowledge of the processes of deterioration, imperfect means of inspection, monitoring, and evaluation, and therefore the risk of unanticipated failure (such as the catastrophic failure of a supporting element). Therefore, the indices used to measure facility condition in this report have a probabilistic or stochastic dimension, expressed either by the mean (or expected value) of condition at some future time and the standard deviation of that estimate, or by the probability of failure of a lock component at some future time.

80. Since locks contain different structural and operational features, separate indices can be defined for each of these major subsets of components. Researchers have the option to either work with a set (or a vector) of condition indices or combine them (according to some empirically established formula) to compute a single index for the lock overall. For purposes of illustration three major categories of features were chosen to evaluate the condition of a lock: gates, walls, and mechanical equipment. (At a recent review meeting, lock maintenance engineers suggested that valves should constitute a fourth category. Valves will therefore be included in future research.)

81. These selections are tentative and await further research to define appropriate lock indices and methods, technologies, and frequencies of measurement. Nevertheless, they will serve as adequate examples of the analytic framework of the REMR Management System and provide an initial basis for discussion. Combining these suggestions with the previous discussion on the treatment of uncertainty, the following measures of facility condition can be used in this preliminary analysis:

a. Expected value of the gate condition index.

b. Standard deviation of the gate condition index.

c. Expected value of the wall condition index.

d. Standard deviation of the wall condition index.

e. Probability of failure of mechanical equipment.

These measures recognize the variability inherent in measures of condition, and the different physical and operational characteristics of these several components of locks. This vector of lock condition is used in the relationships developed in the following section.

Predicting REMR Requirements

82. Frequencies of REMR activities are estimated from the rate at which facilities deteriorate and the particular REMR standards or policy applied to those facilities, as shown in Figure 9 in Part II. This approach assumes that REMR activities can be classified and structured in a form suitable for inclusion in models of deterioration and can be related to standards and policies of facility maintenance, repair, and rehabilitation. The extent to which current data support this approach, or suggest other approaches, is described in the following sections.

Analysis of existing procedures

83. Information regarding the frequency of REMR activities is contained in the maintenance guidelines promulgated by the Chief of Engineers and the historical record of expenditures. Bear in mind, however, that historical records reflect what work was performed, not necessarily what work should have been performed, and that policy guidelines represent a generalized ideal, not necessarily what was carried out at each facility.

84. Guidelines for maintenance practice for locks and dams are summarized in Table 8 (Engineer Regulation (ER)-1130-2-303 1967). These recommendations are prescriptive, based upon previous experience, manufacturers' specifications, and common sense. However, managers have no way of gauging if these intervals are excessive or if more maintenance could save major repair costs at some time in the future. It is this type of question that could be addressed by facility performance relationships as discussed in Part II.

85. Some work has been done to study the historical performance of REMR activities, but to date these reviews have not been extensive, and no conclusions can yet be drawn. For example, a site visit to Maxwell Locks and Dam on the Monongahela River in January 1986 indicated that the facility, opened in 1965, has required almost no major repairs in 20 years of service. The maintenance schedule managed at the site office includes roughly 200 tasks

Table 8

Maintenance Frequencies Specified by Core Guidelines

Parameter	Daily	Weekly	Monthly	Bimonthly	Quarterly	Semiannually	Annually	Biannually	Six Years	Unscheduled
Lock gates										
Mitre								x	x	
Lift							x	x		
Rolling								x	x	
Sector & Tainter								x	x	
Lock valves								x	x	
Trash screens									x	
Tank & chambers								x	x	
Seals & liner plates								x	x	
Guide/bearing rollers						x	x			
Anchorage eye bars						x	x			
Gudgeon pin & casting		x				x				
Pintle assembly								x	x	
Quoin & miter assemblies								x	x	
Mitering devices		x					x			
Operating machinery		x					x			
Tow haul units		x					x			
Dewater facilities							x			
Lock passages										x
Fender booms	x						x			
Life skiffs		x				x				
Life rings							x			
Safety blocks							x			
Guide walls							x	x		
Navigation aids										x
Navigation channels							x			x
Channels							x			
Lined							x			
Cleared							x	x		
French cleared							x	x		
Excavated						x	x			
Trunnions & pins								x	x	

conducted at various intervals. Good maintenance no doubt plays a role in this good performance. Yet, it is difficult to attribute all such benefits to maintenance in the absence of supporting data, since good quality control during construction and the operating environment at Maxwell may also have contributed.

86. Various facilities perform REMR work differently, but similarities appear in their management approaches. Components of facilities or individual tasks are represented on file cards. Each time the crew performs work, the date, task, and comments are recorded on the card. It is from such files that an understanding of the historical performance of REMR may be built. Again, however, this historical experience is limited and does not by itself allow development of the principles suggested in Part II. Records at locks and dams reviewed to date do not firmly establish the causality between deterioration and the need for REMR, nor do they suggest that existing policies account for prior levels of maintenance.

Proposed models of requirements

87. Predictions of REMR requirements are structured analytically within models that relate facility deterioration to standards that specify what activities should be carried out and when. These models are grouped around broad classes of activities that correspond to the different types of preventive or remedial work performed in the field. In future research, these models may also incorporate different technologies or other factors affecting productivity and cost and may include the quality of work performed or the concurrent scheduling of work (e.g., to coincide with the planned dewatering of a lock). For now, all REMR activities will be assumed to be scheduled solely according to the demand for work, a function of the predicted condition of the facility and the governing REMR policy specified by the manager.

REMR activities

88. REMR activities are defined by the Corps of Engineers as follows (Scanlon et al. 1983):

- a. Repair. Restoration of damaged or deteriorated elements to serviceable conditions, normally performed while a facility remains in service.
- b. Evaluation. Determination of the condition, degree of damage or deterioration, or serviceability of a facility; and, where appropriate, indication of the need for repair, maintenance, or rehabilitation.
- c. Maintenance. Actions that either prevent or delay damage or deterioration or both, or correction of deficiencies where such remedies will preclude the need for early repair or rehabilitation.
- d. Rehabilitation. Major modifications that if not performed could result in unserviceability, and during which activities the facility is normally out of service.

89. These definitions of REMR activities include a spectrum of preventive or corrective actions, ranging from relatively minor annual or periodic actions (evaluation and maintenance) to more major actions (repair and rehabilitation). These distinctions are useful in facility management, since different scales of work imply different technologies of prevention or correction, different levels of cost, different staffing and crew needs, different scheduling and logistical requirements, different funding sources, different impacts on users, etc. Models of facility condition and of the costs and impacts of REMR policy are therefore structured around these various classes of activities.

90. In addition to estimating the costs and benefits of different policies governing each of these activities, a REMR Management System can also examine the interactions among these different responses to facility needs (e.g., the trade-offs between periodic maintenance versus capital repair or rehabilitation). Note also that evaluation can be explicitly included within this framework, since better knowledge of facility condition (through inspection or monitoring) can provide early warning of impending damage or failure, and is thus a form of prevention.

91. These four basic REMR activity classes will be used as the basis of development of a Management System for locks. Refinements to the four basic activity classes may be introduced later to reflect different analytic treatments. For example, the term "major rehabilitation" will be used to denote those projects that restore a facility to its as-built or new condition. This means that the improvement is so substantial that the condition indices of the facility can be reset to their initial values. "Minor rehabilitation" and repairs will denote some lesser correction. In Part V "scheduled" versus "unscheduled" work will be discussed to assess whether or not the repairs could have been foreseen. Again, the intent is not to split hairs in the definitions of REMR activities, but rather to draw some useful distinctions in how to predict and analyze the need for different types of work.

Deterioration models

92. Deterioration models predict changes in the indices of facility condition over time as functions of facility use, environmental and aging effects, and the REMR policy specified. The models presented in this section are preliminary and are intended primarily to illustrate how the concepts of

life-cycle costing and demand-responsive maintenance introduced in Part II may be incorporated within analytic expressions. In particular, these expressions capture the demand for REMR arising through facility damage and deterioration, the role of REMR policy in defining management's response to this demand, and the contributions of evaluation, maintenance, and repair to mitigating future damage and deterioration. These predictions of REMR requirements form the basis for the subsequent calculations of REMR-related costs.

93. Three types of deterioration models are developed. The first predicts the expected value of the gate or wall condition indices. The second estimates the standard deviations of these indices over time. The third computes the probability of failure of mechanical equipment. Preliminary analytic expressions for each of these models are presented in the sections below.

94. Expected value of condition index. The expected value of the condition index (CI) for gates and walls is given by:

$$CI[t] = CI_0 - a_1 * \exp\left(b_1 * t^{0.5}\right) \tag{1}$$

where $CI[t]$ = the condition index in year t

CI_0 = the initial condition index

a_1, b_1 = coefficients

Time is assumed to be a surrogate for several factors that affect lock damage and deterioration: quality of design and initial construction (or of subsequent reconstruction or major rehabilitation), the type and extent of lock usage, aging and time-dependent changes in materials properties, and environmental effects (temperature, water intrusion, and chemical attack). Subsequent research may shed light on the respective contributions of these factors to declines in the condition of lock gates and walls, and how they can be best represented analytically. For now, the simple time-related function in Equation 1 will suffice to illustrate the operation and use of a REMR Management System.*

* The exponential of the square root of the time was found to yield a very reasonable rate of deterioration in the expected value of condition, more gradual than an exponential decay based simply on time itself.

95. Standard deviation of condition index. The standard deviation of the condition index is assumed to vary with time, the policy governing routine maintenance and evaluation, and the performance of repair and rehabilitation activities. This relationship is structured as a Markov process, in which the standard deviation of the condition index in any given time period is assumed to be a function solely of the standard deviation in the preceding time period and the level of REMR activities performed in year t:

$$\sigma[t] = \sigma[t-1] * \delta \quad \text{for } t \geq 1$$
$$= \sigma_0 \quad \text{for } t = 0 \tag{2}$$

where $\sigma[t]$ = the standard deviation of the condition index in year t

δ = a variable that reflects the change in standard deviation of condition as a function of REMR activities, where $\delta > 1$

σ_0 = the standard deviation of the condition index in year 0

Additional comments on the ways in which REMR activities interact to influence this relationship will be given in a subsequent section.

96. Probability of failure of mechanical equipment. The probability of failure of mechanical equipment is given by an increasing exponential function of time. The relationship is similar to that for the expected value of the condition index in that time serves as a surrogate for a number of technical, usage, environmental, and aging variables. This deterioration function is given by:

$$\text{Mfail}[t] = \text{Mfail}_0 * \exp\left(a_2 * t^{0.5}\right) \tag{3}$$

where Mfail[t] = the probability of failure of mechanical equipment in year t

Mfail_0 = initial probability of failure of mechanical equipment when it is new (t = 0)

a_2 = a coefficient

97. Effects of REMR activities. In an analytic sense, REMR activities affect not only the values of specific variables (e.g., δ in Equation 2) but also the way in which Equations 1 through 3 must be interpreted. The reason is that activities such as repair or rehabilitation create discontinuities or

steps in the deterioration functions. Thus, while the basic concepts underlying the approach to deterioration are reflected in Equations 1 through 3, some refinements are needed to account for changes due to past REMR activities. The interpretation of δ in Equation 2 needs to be discussed. The effect of REMR activities on the deterioration functions are covered in the following paragraphs.

98. One major consideration in all REMR deterioration models is the effect of discontinuities in the relationship between condition versus time. The discontinuities resulting from repair and rehabilitation produce an immediate and significant increase in the facility's condition index. Analytically this is important, because it represents an interruption in the historical deterioration trend. The way to manage this problem in the preliminary models for locks is illustrated in Figures 19 through 21.

99. Figure 19 is a plot of the elementary deterioration function for the mean condition index over time as given by Equation 1. Figure 20 shows essentially the same function, but interrupted by a repair or rehabilitation at time T. (Whether repair or rehabilitation, and whether minor or major, would be indicated by the extent of improvement in the mean condition index.) The question is: What is the rate of subsequent deterioration following the repair or rehabilitation? The assumption for both of these activities is that the rate of deterioration is uniquely coupled with the value of the CI itself. This is shown graphically in Figure 20 where the slope of the deterioration curve following repair or rehabilitation is equal to the slope of the curve at that same value of CI prior to repair/rehabilitation.

100. This assumption is based on a concept of "equivalent facility age," where this equivalent age would be given as the time between initial construction (or reconstruction or complete rehabilitation) and the time at which the condition index first intersects the reference value CI. In Figure 20, the equivalent age is denoted by m. In effect, the repair or rehabilitation performed at time T restores the facility to a condition it enjoyed at an earlier time m. The slope of the deterioration curve (from Equation 1) would be given by:

$$-a_1 * b_1 \exp\left(b_1 * m^{0.5}\right) \qquad (4)$$

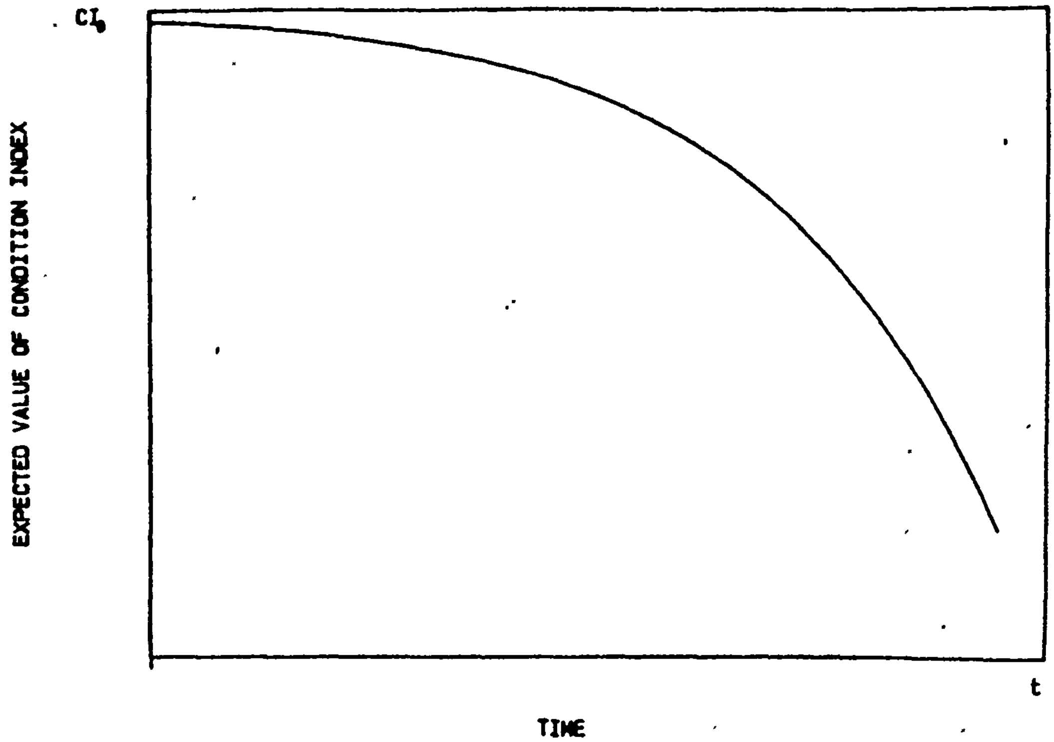


Figure 19. Deterioration of condition index with time

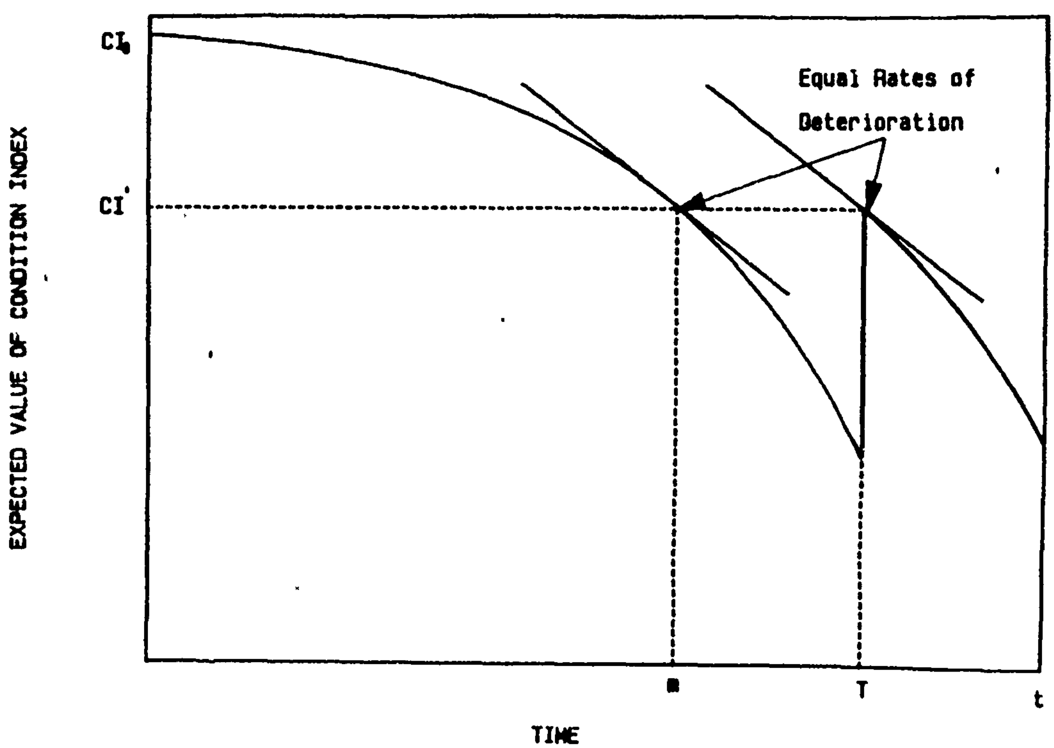


Figure 20. Effect of repair or rehabilitation on the condition index

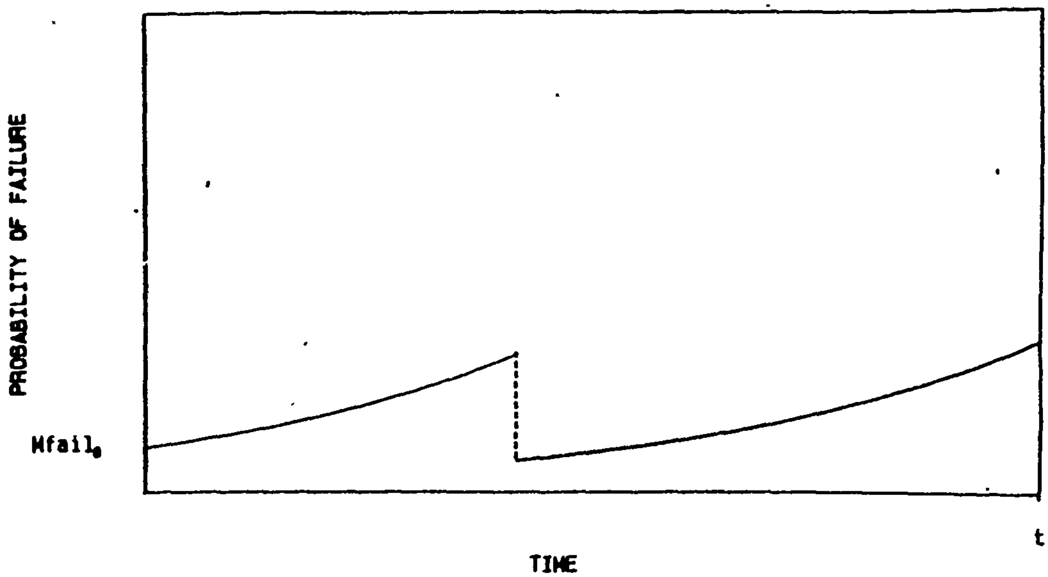


Figure 21. Trend in the probability of failure of mechanical equipment over time

Equation 1 can now be generalized as follows:

$$CI[t] = CI_0 - a_1 * \exp\left(b_1 * m^{0.5}\right) \qquad (5)$$

where m now denotes the (equivalent) age of the facility (i.e., the time since the last new construction, reconstruction, or major rehabilitation).

101. An analogous argument holds for the probability of failure predicted by Equation 3. Introducing the concept of equivalent age yields the following expression illustrated by Figure 21:

$$Mfail[t] = Mfail_0 * \exp\left(a_2 * m^{0.5}\right) \qquad (6)$$

Note that the expected value of facility condition and the probability of mechanical failure (represented by Equations 5 and 6, respectively) capture the effects of only those REMR activities that change the magnitude of the condition index (repair and rehabilitation). They do not directly reflect the impacts of routine maintenance or evaluation. These activities, together with

repair and rehabilitation, are reflected in the computation of the standard deviation of the condition index over time in Equation 2, specifically through the variable δ. The effects of evaluation and routine maintenance will be discussed first, followed by the effects of repair and rehabilitation.

102. If in some time interval there is no rehabilitation or repair and policies governing routine maintenance and evaluation remain constant, then the variable δ likewise remains constant (and greater than 1). The trend in standard deviation computed by Equation 2 is therefore as shown by Curve 1 in Figure 22. When routine maintenance varies, δ is a quadratic function of the difference between actual and maximum routine maintenance as given by:

$$\delta = a_5 + b_5 * (\mathrm{Max[Routine]} - \mathrm{Routine}\,[t])^2 \tag{7}$$

where a_5, b_5 = constants

Max[Routine] = a value representing the maximum level of routine maintenance effort

Routine[t] = the routine maintenance policy in year t

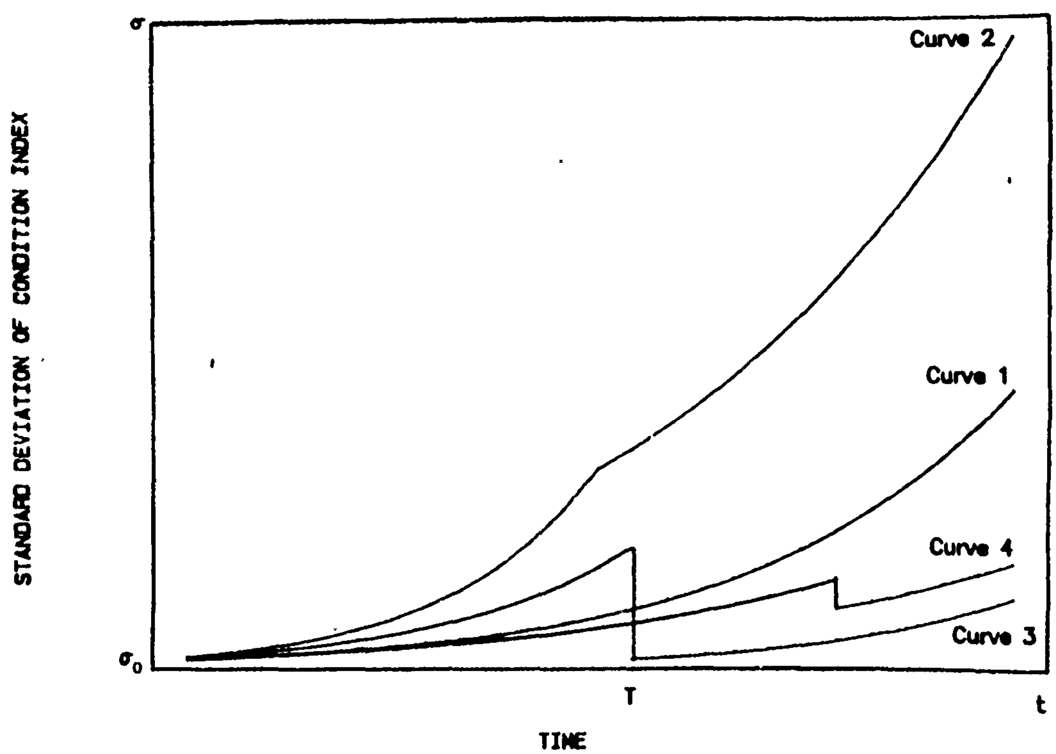


Figure 22. Trends in the standard deviation of condition index with time

This scenario is illustrated by Curve 2, where the level of routine maintenance is constant at some value in the earlier part of the facility's life and increases to a new constant value in the later part.

103. The effects of repairs or rehabilitation again manifest themselves as discontinuities in the analytic functions; the height of the discontinuity (reflecting the reduction in the standard deviation of the condition index) denotes the type of action undertaken. Thus, major rehabilitations restore the standard deviation of the condition index to its original value σ_0 as shown by Curve 3 in Figure 22. Minor rehabilitations or repairs are assumed to reduce the standard deviation by some proportion, as shown by Curve 4 in Figure 22.

104. Figure 22 and Equations 2 and 7 -epresent, in a limited way, the interactions among the different REMR activities that influence facility performance and cost. This is a characteristic of the demand-responsive approach described in Part II and is important to the ability of management to assess trade-offs among different REMR policies. These points will be used to illustrate the prototype Management System discussed in Part V.

Standards and policies

105. REMR policies for repair or rehabilitation may be expressed through "quality standards" defining thresholds at which work should be performed. The interaction between two quality standards, Q_1 and Q_2, and respective facility conditions is illustrated in Figure 23. The different quality standards result (not unexpectedly) in two different trends in the expected value of facility condition over time. Using a simple time average for illustration, the higher quality standard Q_1 results in a higher average system-wide condition C_1. Also, the expected frequency of repair or rehabilitation under Q_1 is greater than that under Q_2, in that $t_1 < t_2$.

106. In Figure 23 it is assumed that all current REMR deficiencies are fully corrected. A more realistic situation, however, is that at any given time only a portion of the accumulated damage in a facility or system is repaired through REMR. From an analytic perspective this option can be represented by varying the height of the improvement in the expected value of the condition index. Figure 24 illustrates two different intensities of correction for the same quality standard Q. I_1 results in relatively frequent but minor correction while I_2 undertakes less frequent but major repair or

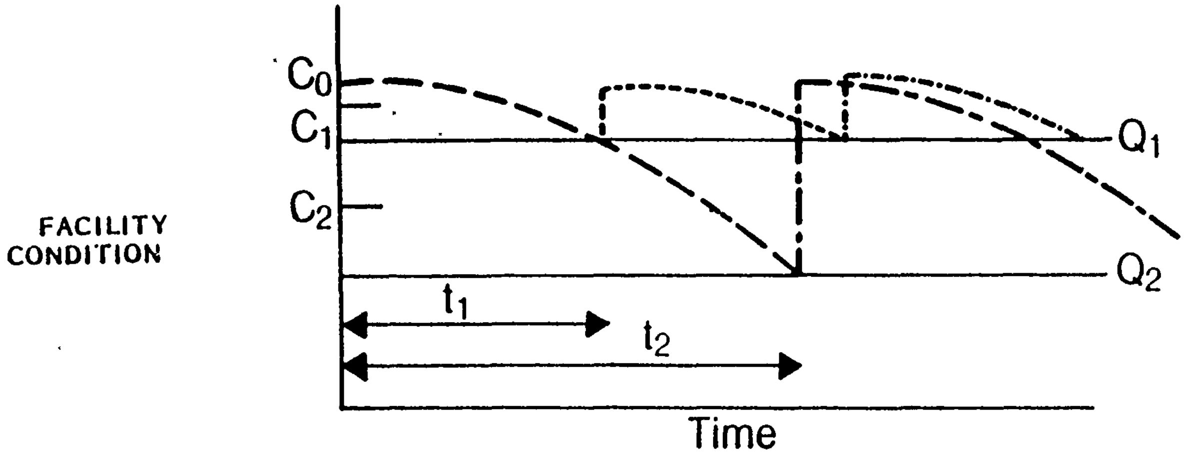


Figure 23. Quality standards defining thresholds of REMR performance

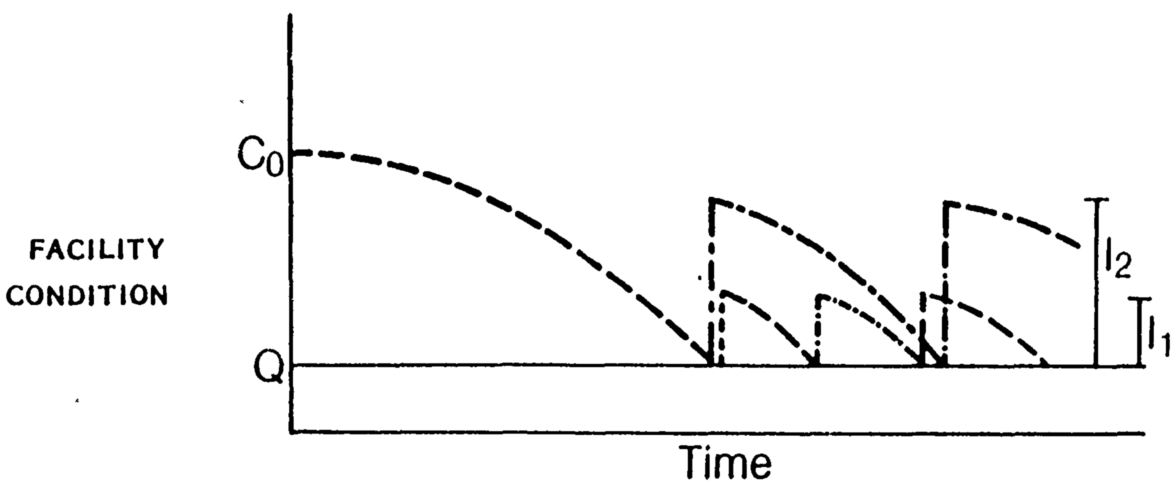


Figure 24. Different improvements due to repair or rehabilitation for a given quality standard

rehabilitation. Note that neither option is sufficient to restore the condition index to its initial value following construction.

107. Variations in the improvement of the condition index that are illustrated in Figures 23 and 24 provide easy ways to represent the differences among different REMR activities. For example, the situation in Figure 23 would denote two policies of major rehabilitation (or reconstruction) in which the rebuilding efforts commence when the facility condition index falls to a value of either Q_1 or Q_2 (the decision between them to be made by the manager). In Figure 24, the I_1 curve corresponds to a repair policy that is invoked when the condition index reaches a value of Q; the I_2 curve corresponds to a policy of minor rehabilitation that is also invoked when the condition index reaches Q.

108. Clearly, a widely ranging set of REMR policies can be defined by varying <u>both</u> the set of REMR activities to be used (to control the amount of improvement in the system) and the quality standards Q for each of these activities (to control the thresholds at which each respective activity is invoked). Combinations of these choices of quality standards and activities would result in policies that differ considerably in their cost, frequency, and intensity of work, and the condition history of the facility. In theory, different policies could be applied to different classes of facilities or to different components of a facility, and the policies for a given facility could be varied over time.

109. Up to now, this discussion has focused on those activities that affect the expected value of condition index: repair and rehabilitation. Although routine maintenance and evaluation do not affect the expected value of the condition index, they do affect the standard deviation of the index over time. Therefore, standards for routine maintenance and rehabilitation are expressed in a different way (see Equation 7). First, maintenance policy is calibrated to some quantitative scale, as implied by the definition of a "maximum" level of maintenance, Max[Routine]. A 0 to 10 scale is used for convenience. Second, this scale can encompass a number of attributes of routine maintenance and evaluation policy (e.g., its frequency, quality of work performed, completeness, intensiveness, etc.). Third, the better the maintenance policy, the less likely premature deterioration or failure of the facility will occur (i.e., the better its reliability, since at any future time the standard deviation of the condition index will be smaller).

General concepts

110. In Figures 23 and 24 the effort devoted to REMR activities governed by a quality standard (Q) is a function of both the frequency of REMR work (proportional to 1/t) and the amount of improvement (I) in the condition index each time a repair or rehabilitation is performed. The costs of different REMR policies (in which either Q, or I, or both may vary) may then be computed by calculating the costs to accomplish various improvements, discounting these at an appropriate rate according to their projected time of occurrence (t), and summing the discounted totals for each policy alternative. Similar calculations apply to the performance of routine maintenance and evaluation. The level of effort and costs of these activities are sensitive to the maintenance policies specified for each year in the analysis period.

111. The measure of expected system condition (C), and therefore the extent of improvement may be in terms of serviceability indices, damage indices, or indices based upon nondestructive tests. Regardless of the measure of improvement employed, it is obvious that an improvement in condition (or, more correctly, the restoration of some or all of the previous condition) must be accomplished by the correction of a certain amount of damage.* The explicit measure of damage corrected (e.g., arresting corrosion, replacing worn components, patching spalled concrete, repairing mechanical equipment) is called the REMR workload, W. In mathematical terms, an improvement in condition I implies a particular REMR workload W, or $I \geq W$. The units of W are appropriate to the particular REMR activity that has been performed. In some cases the units of W and I may be identical, but more generally they will differ, and a function must be defined to relate I to W.

112. REMR workload provides the basis for estimating REMR costs, as shown in Figure 25. A production rate (e.g., average number of damage units repaired per hour or per day) may be applied to a given workload to obtain overall crew time requirements. Workload and crew time may be translated into

* Improvements in the expected value of the condition index will generally be accomplished by some corrective REMR action. The benefits of preventive REMR activities will be reflected in the reduction of the standard deviation of the condition index (Equation 2).

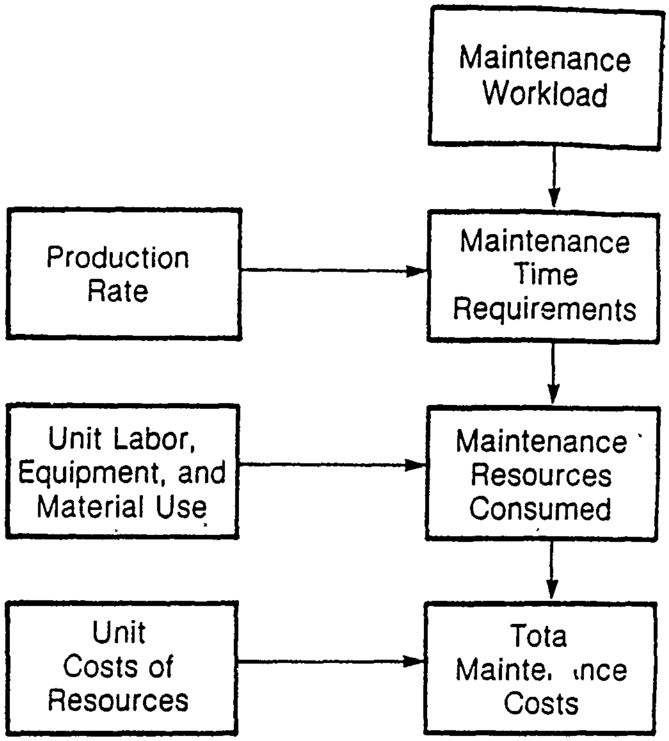


Figure 25. Calculation of REMR costs

resources consumed through unit labor, equipment, and materials or energy usage (e.g., number of laborers or pieces of equipment per crew, or quantity of materials or energy required per unit of damage repaired). These values are a function of the REMR technology employed, quality of crew organization and management, and quality of work performed. Finally, these resource requirements may be multiplied by the respective unit costs of labor, equipment, materials, and energy to obtain total REMR costs.

113. The relationships in Figure 25 point to the supply side of REMR management and are similar to models employed in contemporary facility management systems. The difference between the approach in Figure 25 and the approach used in many existing systems is in the estimation of the workload. Although many current systems predict workload directly from past experience (generally in terms of an average annual workload requirement), this system predicts it based on demand-side considerations of the system condition and REMR policy. The separation of demand-side (Figures 23 and 24) and supply-side (Figure 25) contributions to REMR costs is a particularly valuable

management capability because several aspects of facility management and use may be changing simultaneously.

114. For example, the demand-side relationships in Figures 23 and 24 account not only for the variations in REMR policy, but also for the effects of changing use patterns for locks, unusually adverse weather, chemical or other environmental influences, and changes in lock design and construction standards and practices. For a given REMR policy, the contributions of these effects to REMR costs are transmitted via changes in the predicted REMR workload.

115. On the other hand, the supply-side relationships in Figure 25 account explicitly for changes in REMR technology; work practices; organizational, management, and supervisory characteristics; the resulting crew productivity; and the unit costs of resources employed in REMR (which can be affected by inflation and project scheduling). The contributions of these factors to total REMR costs are superimposed upon, but remain distinguishable from, the effects attributable to total workload arising from the demand for REMR.

116. The approach represented by Figures 23 through 25 therefore represents a very powerful and flexible treatment of REMR requirements and costs. It can respond to different management needs and address policy questions that are not within the scope of contemporary facility management systems (e.g., the benefits to REMR to be conferred by changes in design standards, construction quality, or REMR technology). However, as described in the following sections, the data necessary to support the calculations implied by Figure 25 have not yet been obtained.* Therefore, other approaches to estimating REMR-related costs need to be investigated for use in the interim.

Analysis of REMR cost data

117. Historical cost data obtained from the Corps of Engineers were reviewed to assess the level of aggregation, reliability, and characteristic trends of available statistics. The analyses based upon these data, which

---

* Experience in highway maintenance management suggests that the data and analyses to implement the calculations in Figure 25 are not difficult to obtain; the issue is simply that this information has not been collected or structured in the way that is required. The major challenges in pursuing a demand-responsive approach for locks are (a) to define appropriate condition indices and (b) to develop and calibrate the damage or deterioration functions in Equations 1 through 7 for use as shown in Figures 23 and 24.

will be described below, do not yet fulfill the concepts developed in Part II, although they represent a first step. These results are much less detailed than the cost models envisioned in Figure 25 and cannot convey explicitly many of the interactions among supply- and demand-side factors discussed earlier. Not only do they present a much more aggregate picture of cost trends over time, but also their explanatory power is statistical rather than cause-and-effect.

118. Nevertheless, without the data needed to develop the models in Figure 25, these statistical methods are the best available tools for analyzing costs. Furthermore, their application may reveal long-term patterns in REMR cost histories that would be very useful in moving toward the more detailed models in Figure 25. The following sections review the cost data from lock project files and present and interpret the results of statistical analyses of these costs.

Costs of operations, inspection, and routine maintenance

119. A Corps study of over 100 annual operational and routine maintenance costs shows that operational costs are correlated with lock use and routine maintenance costs with the size of the lock chamber (Louis Berger and Associates 1981). All costs include labor, materials, and utilities. Operational costs cover routine lock operation and maintenance costs include nonemergency repair and cleaning. The relationships between operational costs and use and between routine maintenance costs and chamber size are presented in Figures 26 and 27, respectively.

120. These correlations are not surprising as locks handling more lockages are expected to incur higher utility costs and require more personnel for operations. Similarly, larger lock chambers are expected to require more personnel for inspection and consume additional materials for repair. Economies of scale are present for larger chambers as shown in Figure 27. These costs do not, however, reflect two important effects. First, labor costs, which account for a major part of operating and maintenance costs, vary significantly from region to region. Second, as discussed earlier, analyses of historical data do not reflect current policy or condition, nor can they account for future changes in policy.

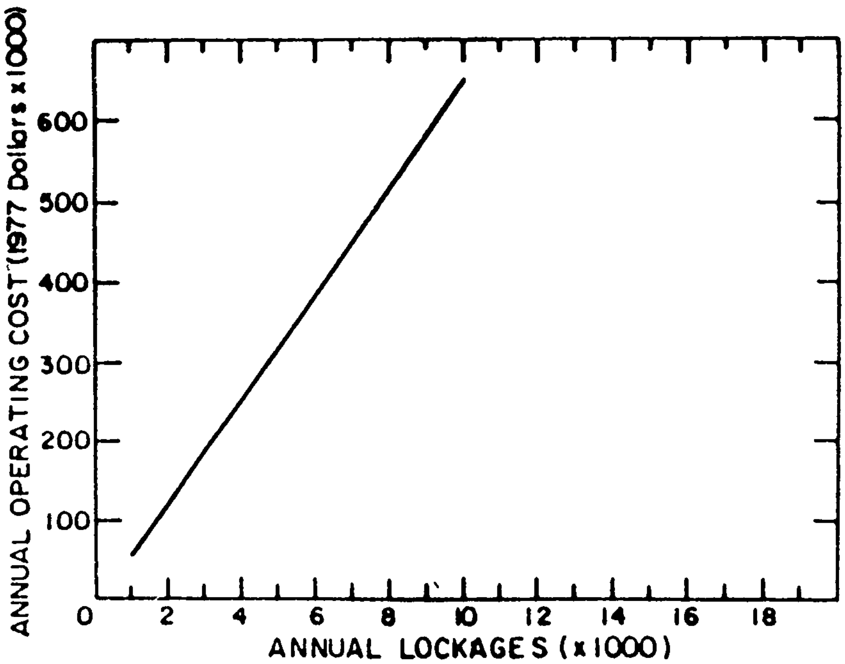


Figure 26. Annual operating costs as a function of annual lockages (Source: Berger, Louis, and Associates, Inc. 1981. "Engineering Analyses of Waterways Systems," Final Report, US Army Corps of Engineers [part of National Waterways Study].)

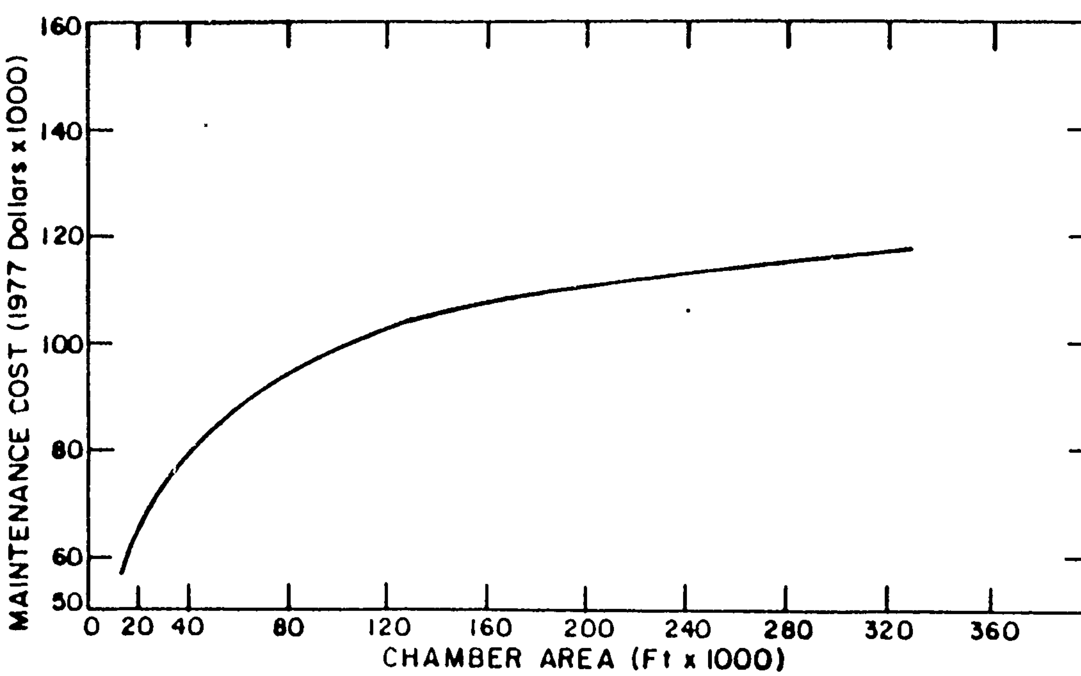


Figure 27. Annual routine maintenance costs as a function of chamber area (Source: Berger, Louis, and Associates, Inc. 1981. "Engineering Analyses of Waterways Systems," Final Report, US Army Corps of Engineers [part of National Waterways Study].)

Costs of repair and rehabilitation

121. Data sources and description. Expenditure data for repair and rehabilitation were obtained from reconnaissance reports obtained from the Pittsburgh District for the Emsworth, Montgomery, and Dashields locks and dams on the Ohio River. A line item entry in the Montgomery report is shown in Figure 28 as an example of the information contained in these documents. The years sampled for our analysis and histories of major rehabilitation are summarized in Table 9.

122. Table 10 summarizes the estimated annual use for each lock in terms of the number of tows, barges, lockages, and tonnages annually. As this table shows, the three locks experience similar levels of use--not unexpectedly, since these facilities are adjacent to each other on the same river. Furthermore, these projects are maintained by the same District, and they experience similar environmental conditions. These use and environmental factors display no significant differences in REMR demand. The roles of design standards and construction quality are not reflected in Tables 9 and 10, nor are differences in the quality of REMR activities performed, the extent and quality of site supervision, etc.

123. The expenditure data are then disaggregated to the extent possible* into three categories: dam expenditures, lock expenditures, and other expenditures. Included in "other expenditures" are items not related to the age or use of the actual lock and dam (e.g., costs in supplying municipal water or replacing the roofs of buildings).

124. The historical expenditures for lock repair and rehabilitation projects at each location are plotted in Figures 29 and 30. Figure 29 displays the actual (current) expenditures; Figure 30 reduces these expenditures to constant 1977 dollars, deflated by the Engineering News Record Construction Cost Index.

125. Both figures show a "saw-toothed" pattern of expenditures with alternating positive and zero expenditures. The positive expenditures in current dollars in Figure 29 increase with time due to inflation. Before 1950, few projects were over $100,000. The positive constants do not show a clear trend. The modal value is around $100,000 with major projects being clearly

---

* Aggregate costs for some components prevented detailed analysis of lock expenditures individually for gates, walls, and mechanical equipment.

Year: 1955

Repair: Repair river walls, valves and river chamber miter sills.

Cost: 33,332

Lock Shutdown Duration Days/

Land or River Chamber: 9/RC

Figure 28. Sample entry from reconnaissance report for Montgomery

Table 9

Lock and Dam Characteristics

Data Set	Years of Data	Chamber Size (sq ft)	Rehabilitated
Dashields	1933-1983	86,160	1940, 1952
Emsworth	1931-1976	86,160	1931, 1937, 1956
Montgomery	1936-1982	86,160	1966

Table 10

Estimates Annual Lock Usages

Lock and Dam		Tows	Barges	Lockages	Tonnage
Dashields	Main	3,914	26,022	4,492	16,975
	Auxiliary	799	1,079	2,484	463
	Total	4,713	27,101	6,976	17,438
Emsworth	Main	4,310	24,531	5,271	15,875
(estimated)	Auxiliary	793	2,028	2,568	1,057
	Total	5,103	26,559	7,839	16,932
Montgomery	Main	3,678	25,742	4,552	17,690
	Auxiliary	635	1,362	2,506	712
	Total	4,313	27,104	7,058	18,402

evident in 1938 and 1958 for Emsworth, 1966 for Montgomery, and 1941 and 1953 for Dashields (Figure 30).

126. Average expenditures for repair and rehabilitation. Average expenditures for repair and rehabilitation are given in Table 11 and are computed from the histories of constant dollar expenditures given in Figure 30. Locks consume most of the expenditures for repair and rehabilitation at the Emsworth and Dashields facilities, with dams accounting for a very small remainder. However, expenditures for repair and rehabilitation of Montgomery Dam represent approximately 40 percent of the total repair and rehabilitation expenditures at that facility. Thus, by focusing on locks, this report has elements of the waterways system that are significant to REMR management, although the degree of that significance varies from one project to another. Also, these data are drawn from the Pittsburgh District for facilities on the Ohio River; it is not yet known how these data compare with the cost histories of facilities with different characteristics that are managed by other Districts.

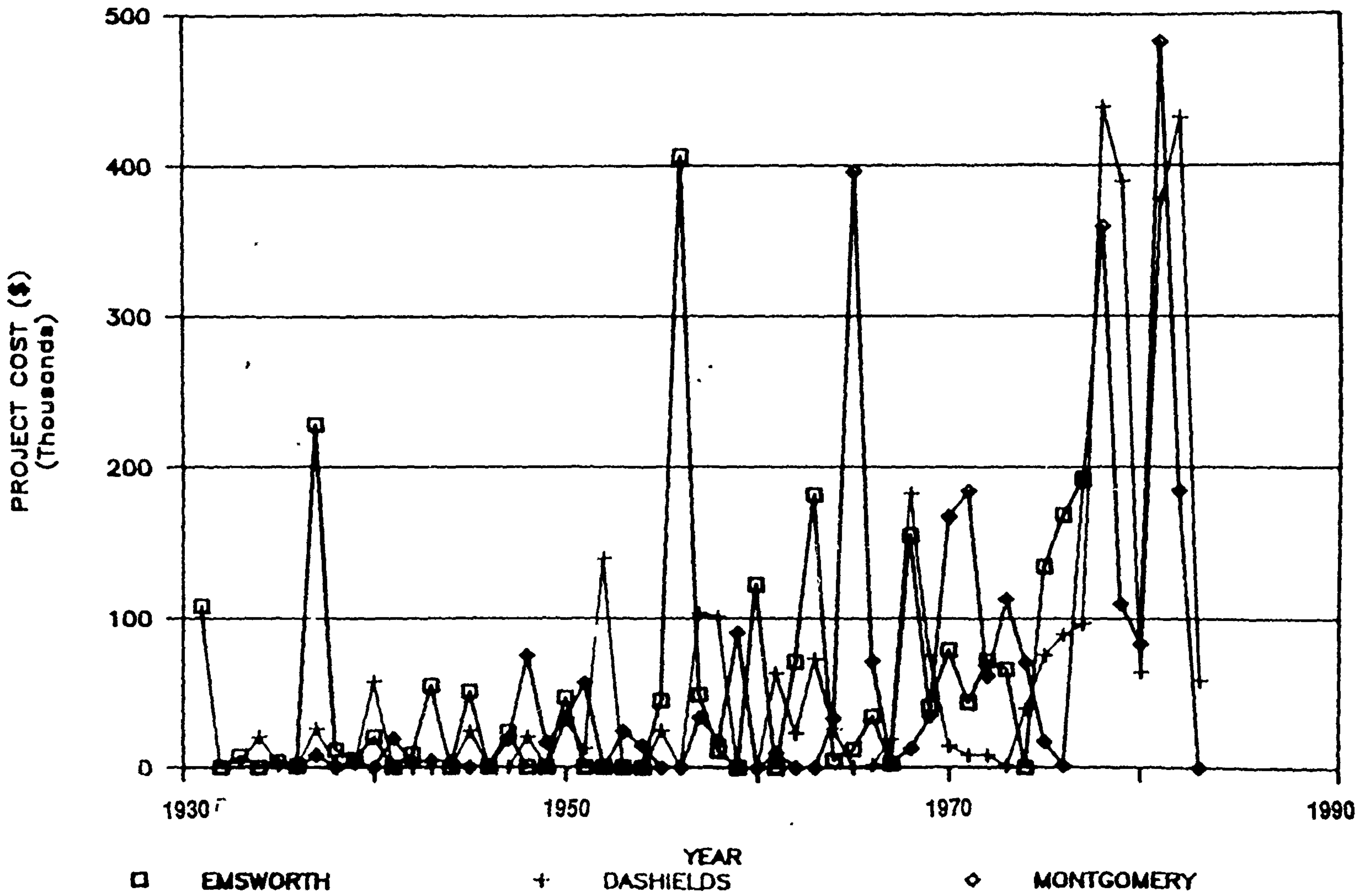


Figure 29. Project costs in current dollars for Emsworth, Dashields, and Montgomery locks

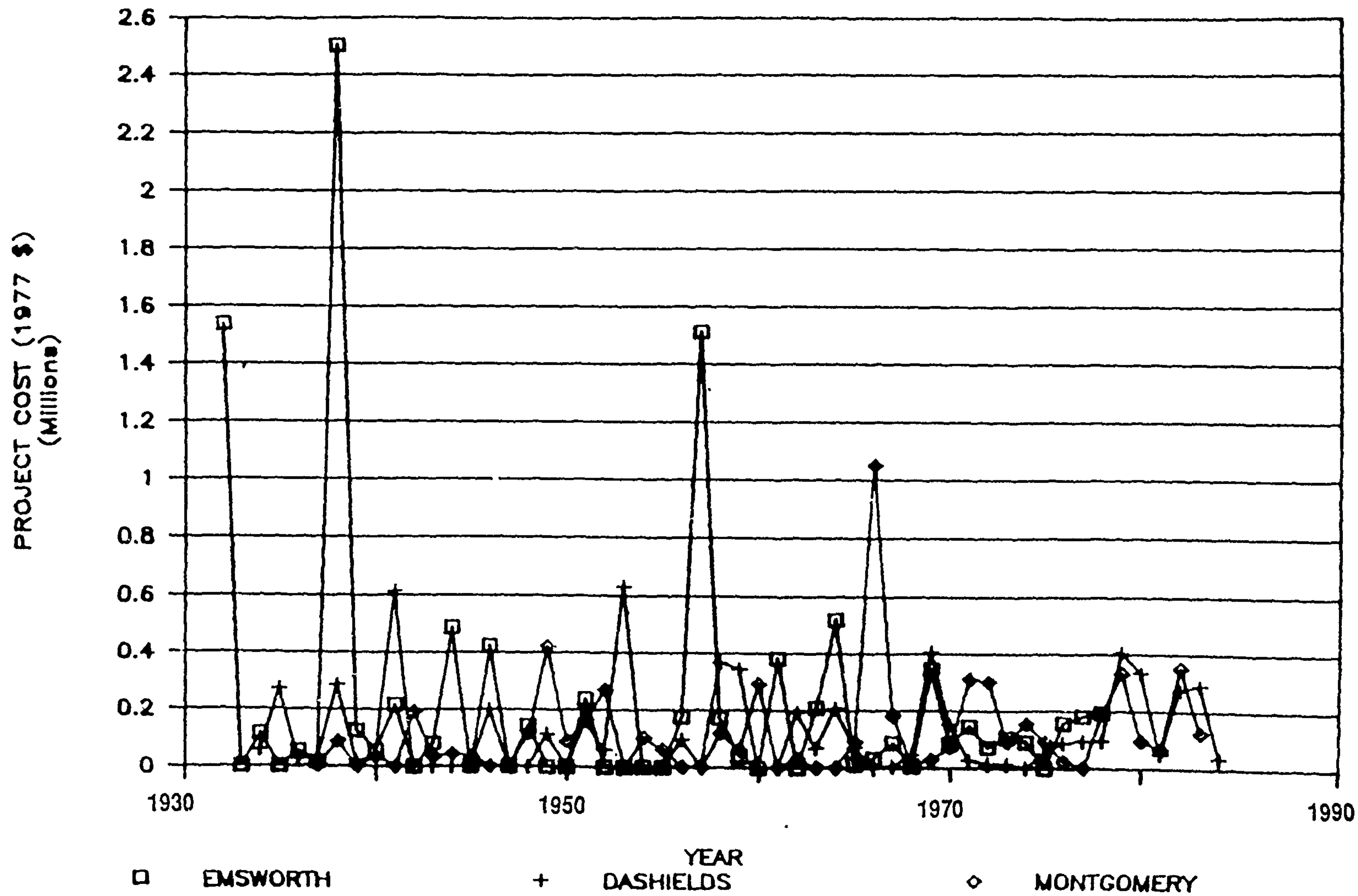


Figure 30. Project costs in constant dollars for the Emsworth, Dashields, and Montgomery locks

Table 11

Average Annual Expenditure (in 1977 dollars)

Data Set	Lock & Dam	Lock Only
Dashields	127,840	122,337
Montgomery	199,130	121,040
Emsworth	230,920	223,490
Average	185,963	155,622

127. Annual expenditures were also disaggregated by major facility component: gates, lock walls, and mechanical equipment. These breakdowns are approximate since recorded expenditures in the reconnaissance reports often pertain to more than one item of the facility. Allocation of costs had to be done somewhat arbitrarily. Further estimates were also made to distinguish between major rehabilitations and more frequent repair and minor rehabilitation activities. As guidelines for this calculation, annual expenditures less than $200,000 (1977 dollars) for gates or walls and annual expenditures less than $150,000 (1977 dollars) for mechanical equipment were assumed to be associated with repair activities; greater amounts denoted minor and major rehabilitation. Average annual costs are summarized in Table 12.

128. Table 12 also shows the average expenditure per project for expenditures under $100,000. Considering the gate expenditures for Emsworth, the average annual expenditure is $102,420, the average annual expenditure for projects under $100,000 is $11,750, and the average project cost for projects under $100,000 is $41,590. Therefore, on an average, repair work of less than $100,000 for gates occurs approximately every 4 years.

129. Although the average annual expenditures computed in Tables 11 and 12 indicate an overall level of funding for repair and rehabilitation, they do not reveal anything about the short-term or long-term variations in expenditures, or their relationship to factors affecting facility condition. While

Table 12

Average Expenditures for Projects

Average of All Expenditures

Location	Gates	Wall	Mechanical Equipment
Dashields	52,880	26,210	32,460
Emsworth	102,420	89,670	32,080
Montgomery	66,870	17,540	36,640
Average	74,060	44,470	33,730
Annual Average of Expenditures for Projects Under $100,000			
Dashields	10,270	7,560	8,850
Emsworth	11,750	7,150	5,270
Montgomery	13,850	5,590	10,070
Average	11,960	6,770	8,060
Average Total Expenditure per Project Under $100,000			
Dashields	30,800	48,180	32,260
Emsworth	41,590	27,400	26,910
Montgomery	38,300	65,420	47,320
Average	36,900	47,000	35,500

regression analysis may be used to identify correlations between expenditures and explanatory variables (e.g., factors causing facility deterioration), it is more prudent to identify any time-related variations in these levels, without attempting to explain them. The following section presents the results of this analysis. Remember that the expenditures shown reflect what work was actually done and when, not necessarily what would have been done in an ideal situation.

130. Time series analyses. Time series models use the past behavior of variables to forecast future values without the use of explanatory variables.

The most commonly used approach was developed by Box and Jenkins (1976). The Box-Jenkins approach was applied to the time series data for Emsworth, Dashields, and Montgomery locks to identify any patterns in the frequency and magnitude of expenditure. The results of the analyses are reported in Appendix A.

131. The analyses of these historical records show that the pattern of expenditures for the three locks is similar, in that the time series models obtained have the same structure and the parameters are of similar magnitude for each lock. These results indicate that the only identifiable and predictable variations in expenditures for repair and rehabilitation are extremely short-term and relatively small in magnitude. Basically, one could estimate the expenditure in any given year simply by knowing the expenditures in the preceding 3 years. Unfortunately, no longer term variations are evident; the 35 to 45 years of data available were insufficient to statistically capture major rehabilitations.

132. Therefore, using the Box-Jenkins model to forecast expenditures beyond 2 or 3 years introduces considerable uncertainty. Thus, the models developed in this analysis cannot be included in the Management System since they do not extend over a sufficiently long analysis period and they implicitly include historical REMR policies that do not permit any variation in the future. However, these analyses have demonstrated at least a consistent pattern of expenditures for each of the locks.

Lock damage costs

133. Lock gates and walls can be damaged by impacts from barges. Although it is Corps policy to recoup costs of repair from responsible barge operators, these unforeseen instances of damage create additional demands for REMR work and expenditures of resources (even if the dollar costs are eventually reimbursed). This fact establishes one reason that lock damage costs need to be included in a REMR Management System.

134. A second aspect of lock damage that is important for Management System design is the fact that the damage is unforeseen and therefore cannot be predicted in time, location, or severity. In this sense, barge impacts are somewhat different from "natural" mechanisms that deteriorate facilities gradually and exhibit progressive damage from year to year. From an analytic standpoint, the uncertain location, timing, and severity of barge impacts

require a stochastic or probabilistic treatment, introducing additional complexity not only into formulation of deterioration and cost models, but also into any optimization procedures that may eventually be included (e.g., to identify optimal REMR policies or technologies). This stochastic element of REMR management of locks represents a unique challenge in Management System design and will likely lead to investigations of operations research and expert systems techniques in future stages of research.

135. To provide some insight into how the stochastic element may be modeled, damage incidents and the cost of their repair given in the Reconnaissance reports since 1960 were analyzed. The average number of damage occurrences per year due to traffic and the average cost to repair such damage are shown in Table 13. The data indicate that a similar number of incidents per year occur at Emsworth and Dashields, but the incidents at Emsworth are much more costly to repair. Similarly, more incidents occur at Montgomery than Dashields, but the severity of the incidents is similar.

136. Based on a chi-square test, the number of occurrences of damage follows a Poisson process. Therefore, damage occurrences are "random" and not related to deterioration or age. In general, damage costs are relatively insignificant compared to total maintenance costs, suggesting that the Poisson process be used to model the damage incidents. This will yield an expected expenditure for repair due to damage for each lock. These costs can then be aggregated at the District level and will be constant for each year.

Table 13

Average Annual Damage Occurrences and Costs

Lock	Average No. of Occurrences per year (since 1961)	Average Annual Cost to Repair Damage (1977$)	Average Cost per Incident to Repair Damage (1977$)
Emsworth	0.47	2,960	6,289
Dashields	0.52	7,830	15,015
Montgomery	1.09	17,150	15,723

Proposed cost models

137. The proposed cost models for routine maintenance and evaluation, lock operations, major and minor rehabilitation, and repair are based on analysis of existing data as described in the preceding sections. However, two new analytic features have been introduced in accordance with concepts presented in Part II and earlier in this chapter: (a) REMR policies have been included specifically as variables affecting the demand for work, and hence its cost, and (b) the role of uncertainty has been explicitly recognized.

138. Including REMR policy as a variable affecting cost is one of the key concepts of the demand-responsive approach developed in Part II. However, cost histories from which the models are inferred implicitly include the specific evaluation, maintenance, repair, and rehabilitation policies and actions that have been followed in the past. Therefore, the models proposed below attempt to adjust these historical trends to account for variations in REMR policy that have been observed. Because the models are preliminary, calibration of the effects of REMR policy on costs requires further research and analysis.

139. Including a stochastic or probabilistic treatment responds both to the way in which evaluation and routine maintenance are proposed to be modeled and to the way in which damage to locks from barges occurs. This treatment can therefore represent repair and rehabilitation activities that respond to unanticipated requirements. The resulting costs will be referred to as unscheduled costs. Predicting unscheduled costs will be illustrated in the example problem presented in Part V.

Scheduled rehabilitation costs

140. Rehabilitation costs are assumed to be proportional to an increasing linear function of the amount of improvement achieved. That is, it costs more to achieve a greater increase in condition or to achieve the same amount of improvement when the facility is in worse condition. The relationships are as follows:

Gate/wall scheduled repair and rehabilitation cost

$$\text{S\_Cost}[t] = \begin{cases} a_6 + b_6 * \Delta & \text{if } \Delta \le \Delta_{max} \\ a_6' + b_6' * \Delta & \text{if } \Delta > \Delta_{max} \end{cases} \qquad (8)$$

where $S\_Cost[t]$ = scheduled maintenance cost in year t

a_6, b_6, a_6', b_6' = coefficients

Δ = amount of condition index improvement in year t

Δ_{max} = maximum amount of condition index improvement that can be achieved by minor rehabilitation.

Note: $S\_Cost[t]$ = 0, if neither minor nor major rehabilitation is done in year t.

Mechanical equipment scheduled repair and rehabilitation

$$M\_S\_Cost[t] = \begin{cases} a_7 + b_7 * \Delta & \text{if } \Delta \le \Delta_{max} \\ a_7' + b_7' * \Delta & \text{if } \Delta > \Delta_{max} \end{cases} \tag{9}$$

where $M\_S\_Cost[t]$ = mechanical equipment scheduled maintenance cost in year t

a_7, b_7, a_7', b_7' = coefficients

Δ = reduction in probability of failure in year t

Δ_{max} = maximum reduction in probability of failure that can be achieved by a minor rehabilitation

Note: $M\_S\_Cost[t]$ = 0, if neither minor nor major rehabilitation is done in year t.

Unscheduled repairs or rehabilitation costs

141. Unscheduled repairs or rehabilitations occur when the condition index is allowed to fall below a minimum standard or the mechanical equipment fails unexpectedly. For gates or walls, the expected value and standard deviation of the condition indices are known. Therefore, if the condition index is assumed to be normally distributed, the probability of the condition index falling below the standard can be estimated and the expected cost of repair computed as follows:

$$US\_Cost[t] = inc\_prob * us\_maint\_cost \tag{10}$$

where $US\_cost[t]$ = expected value of the unscheduled gate/wall maintenance cost in year t

inc_prob = incremental probability of gate/wall condition index falling below the failure condition index standard in year t

us_maint_cost = expected value of unscheduled minor maintenance cost for gate/wall and mechanical equipment in any year

142. Similarly, the probability of mechanical equipment failure is known as the expected cost of repair and can be computed as follows:

$$\text{M\_US\_Cost}[t] = \text{inc\_Mfail}[t] * \text{m\_minor-maint-cost} \tag{11}$$

where M_US_Cost[t] = expected unscheduled mechanical equipment repair cost in year t

inc_Mfail[t] = incremental mechanical equipment probability of failure in year t

us_mech_maint_cost = unscheduled minor maintenance cost for mechanical equipment in any year

Routine maintenance cost

143. Currently, the data from the field include routine maintenance costs with operating costs. In the REMR Management System, however, routine maintenance costs (including evaluation costs) are segregated from operating costs so that the role of maintenance in affecting facility condition can be explicitly analyzed. The proposed cost model is the sum of quadratic functions of the level of routine maintenance given by:

$$\begin{aligned} \text{Routine\_Maint\_Cost}[t] &= a_8 + b_8 * \text{G\_routine}[t]^2 \\ &+ c_8 + d_8 * \text{W\_routine}[t]^2 \\ &+ e_8 + f_8 * (\text{M\_routine})^2 \end{aligned} \tag{12}$$

where Routine_Maint_Cost[t] = routine maintenance cost in year t

$a_8, b_8, c_8, d_8, e_8, f_8$ = coefficients

G_routine[t] = routine maintenance policy for gates in year t

W_routine[t] = routine maintenance policy for walls in year t

M_routine = average routine maintenance policy for mechanical equipment for the entire planning horizon

144. Operating costs. Operating costs are based on the volume and type of traffic. These variables are included in the following model of operating cost:

$$\text{Op\_Cost}[t] = \text{avg\_lockage\_cost} * \text{lockages} * \text{traffic}\ [t] \qquad (13)$$

where Op_Cost[t] = operating cost for lock in year t

avg_lockage_cost = average cost per lockage

lockages = average number of lockages per tow

traffic [t] = traffic in tows/year in year t

145. Damage costs. Repair or rehabilitation costs due to motor vessel damage are based on the average annual damage costs because the probability of damage occurring is assumed to be a Poisson process.

Total agency costs

146. The costs of operations, evaluation, routine maintenance, scheduled and unscheduled repairs, and major and minor rehabilitation are summed to yield total agency costs for REMR in any given year. The occurrence of scheduled rehabilitation in any year is determined by the rehabilitation requirements derived from (a) the prediction of facility condition in that year and (b) the rehabilitation policy specified for that year. The costs of unscheduled rehabilitation are based on the probability of failure or deterioration below a standard and the expected cost of repair. For specified REMR policies and standards, these costs can be computed for each year of the planning horizon and discounted to give total costs. Such discounted cost calculations through a multiyear analysis period will be illustrated in the example in Part V.

PART IV: EVALUATING THE BENEFITS OF REMR ACTIVITIES

Impacts of REMR Policy on Inland Navigation

147. The Corps of Engineers has been directed by Headquarters, US Army Corps of Engineers (HQUSACE) to abide by the Water Resources Council (WRC) Manual of Procedures for Evaluation of National Economic Development (NED) Benefits and Costs in Water Resources Planning (Level C). The purpose of this manual is "to provide federal agencies with a set of procedures that ensures that NED benefits and costs are estimated using the best current techniques, and are calculated accurately, consistently, and in compliance with the Principles and Standards and other applicable economic evaluation requirements" (Federal Register 1979). Two important points regarding this manual should be emphasized:

a. The WRC manual provides an outline of steps for the economic analysis of costs and benefits expected from new projects. REMR operations are mentioned on the cost side only as a portion of project outlay. Despite omitting REMR considerations from the benefit side of the analysis, the manual provides a thorough outline of benefit evaluation procedures which can be adapted to REMR benefit evaluation.

b. The WRC manual requires the use of "the best current techniques," but itself offers no econometric models. The reason for this omission is the transient nature of the models. The best current technique of 1979, the year of the manual's publication, will probably not be the best current technique of 1989. It is up to the various Federal agencies and their contractors to determine the best current techniques.

148. The first part of this chapter discusses the first step of economic analysis by reviewing available models to predict the impacts of waterway project improvements. This review then forms the basis for subsequent studies and model development to predict the consequences of REMR policies.

149. The WRC manual evaluates navigation projects according to the following principle:

> The basic economic benefit of a navigation project is the reduction in the value of the resources required to transport commodities.

150. Four types of navigation benefits are identified and will be discussed in detail in the following sections:

a. Cost reduction benefit (same origin-destination; same mode):

(1) Reductions in costs incurred from trip delays.

(2) Reductions in costs because larger or longer tows can use the waterway (e.g., by channel straightening or widening).

(3) Reduction in costs by permitting barges to be fully loaded (e.g., by channel deepening).

b. Shift of mode benefit (same origin-destination; different mode).

c. Shift of origin-destination benefit.

d. New movement benefit.

Cost Savings Due to Reductions in Trip Delays

151. A number of mathematical models decompose shipping costs into components and then sum the components to determine total costs. The primary components are the fixed costs of capital and overhead and the variable costs of towboat and barge operation.

Northwestern University model

152. The Institute for Water Resources sponsored a major research project at Northwestern University Econometrics Center that resulted in a three-volume study entitled Cost-Benefit Analysis for Inland Navigation Improvements (Moses and Lowe 1970). In a related doctoral thesis, DeSalvo developed the following equation for shipping costs in cost/ton-mile for a tow (DeSalvo 1968):

$$C_{tm} = \frac{(C_t + N_b C_b)}{q} \tag{14}$$

where C_{tm} = cost per ton-mile

C_t = cost per hour of towboat operation

C_b = cost per hour of barge operation (Jumbo hopper type)

N_b = number of barges in tow

q = rate of transport production for a tow, in ton-miles per hour

153. C_t and C_b, available from the Corps of Engineers, determine per hour costs based on data collected from barge firms. The rate of transport production, q, in ton-miles per hour, is determined as follows:

$$q = C * \frac{D}{T_t} \qquad (15)$$

where C = cargo tonnage of tow, in tons
D = distance of trip, in miles
T_t = total transit time for trip

T_t is a summation of five time factors:

$$T_t = T_f + T_L + T_m + T_b + T_o \qquad (16)$$

where T_f = time required to travel distance D at full speed in hours
T_L = locking time, in hours
T_m = make-tow time, in hours
T_b = break-tow time, in hours
T_o = miscellaneous delay time, in hours

154. T_L, T_o, and T_f are the time parameters that would be affected by REMR policy. N_b, number of barges in the tow, is also a function of REMR policy through the influence of channel maintenance on channel width and degree of curvature. Channel maintenance also affects C, cargo tonnage, which can be limited by channel depth. In later sections of Part IV the specific details of these potential impacts of REMR policy on shipping costs will be discussed.

Tow Cost Model

155. The Tow Cost Model is a product of model developments initiated by the OCE, and of several years of testing and refinements made by various elements of the Ohio River Division.

156. The Tow Cost Model (TCM), like the DeSalvo model, decomposes direct shipping cost into barge costs (C_b) and towboat costs (C_t) in dollars per

ton-mile. Whereas DeSalvo accepts these component costs as input, the costs per ton-mile are figured directly in the TCM:

$$C_{bj} = \frac{(n\ e_c\ z_b\ t_j)}{(2\ n\ e_c\ e_l\ e_d\ Y\ D)} \tag{17}$$

$$C_{tj} = \frac{(Z_t\ t_j)}{(2\ n\ e_c\ e_l\ e_d\ Y\ D)} \tag{18}$$

where n = number of barges

e_c = tow capacity factor

z_b = daily operating cost for a barge

t_j = one of 7 time factors, j = 1 through 7, measured in days, as follows:

t_1 = loading and unloading time
t_2 = time spent waiting for access to docks
t_3 = time that barges spend waiting for pickup
t_4 = make-tow and break-tow time
t_5 = link travel time
t_6 = lockage service time
t_7 = lock delay time

2 = factor to account for round trip

e_l = fraction of loaded barges

e_d = barge loading factor, (maximum possible loading/nominal barge capacity)

Y = barge capacity

D = distance between origin destination pair

Z_t = daily operating cost for a towboat

157. To find total barge costs, sum the appropriate t_j factors:

$$C_b\ (\text{total}) = \sum_{j=1}^{7} C_b \tag{19}$$

To find total tow costs, sum the appropriate tj factors:

$$C_t \text{ (total)} = \frac{\sum\limits_{j=4,6,7} (Z_{tm} t_j)}{(2\ n\ e_c\ e_l\ e_d\ Y\ D)} + \frac{(Z_{to} t_5)}{(2\ n\ e_c e_l e_d\ Y\ D)} \tag{20}$$

where Z_{tm} = maneuvering costs for towboat

Z_{to} = line haul operating costs for towboat

158. The TCM equations compare very closely to DeSalvo's when some of the factors are aggregated:

Total round trip distance = 2D (corresponds to DeSalvo's D)

Total tons = $n\ e_c\ e_l\ e_d\ Y$ (corresponds to DeSalvo's C, cargo tonnage)

159. The TCM is more detailed in its decomposition of shipment time. Whereas DeSalvo calls T_o "miscellaneous delay time," the TCM identifies this as 3 components: t_1, t_2, and t_3. These time components do not contribute to towboat operating costs since the towboat arrives to pick up the tow after it is loaded and leaves before it is unloaded. DeSalvo's model lumps all the time factors together for both towboat and barge, overestimating total towboat costs in the process. Yet the two models yield similar results in an analysis of the change in cost for a given change in maintenance policy, since REMR actions would only affect link travel time, lock service time, and lock delay time, the three time components which contribute to both towboat and barge operation time. Any differences between the two would arise from the TCM's distinction between Z_{to}, line haul operating costs for a towboat, and Z_{tm}, maneuvering costs for a towboat. DeSalvo's model makes no such distinction.

160. Another difference between the models is that the TCM includes a factor representing percentage of loaded barges hauled that accounts for return trips by empty barges. DeSalvo omits this factor in his direct cost calculation, but accounts for this decrease in tonnage in a later section of his analysis by adjusting the arrival rate of tows.

161. The last feature of interest in the TCM's shipping cost analysis is the computation of a cargo inventory cost per ton-mile:

$$C_{inv} = \frac{\sum_{j=1}^{7} (Z_c\ t_j)}{2D} = \frac{(Z_c\ T_t)}{2D} \tag{21}$$

where Z_c = inventory cost ($/day/ton) = $(v_c\ h_c)/365$

and

v_c = commodity value($/ton)

h_c = annual holding cost factor

Again, REMR policy would affect the cargo inventory cost only through its effect on enroute time components t_4 through t_7.

National Waterways Study

162. A National Waterways Study (NWS) provides a third sequence of formulas for determining shipping costs (Hochstein, Patton, and Louis Berger and Associates 1981). The NWS accounting procedure is analogous to the TCM cost model in that it divides shipment costs into towboat costs, barge costs, and cargo holding costs, all measured in cost per ton-mile.

163. Costs associated with enroute time are computed from these formulas:

$$C_{tb} = \frac{(c_{tb}\ T_1)}{(2\ n\ U_t\ q\ U_b\ D\ [1 - E])} \tag{22}$$

$$C_b = \frac{(c_b\ T_1)}{(2\ q\ U_b\ D\ [1 - E])} \tag{23}$$

$$C_c = \frac{(c_c\ T_1)}{(2\ D\ [1 - E])} \tag{24}$$

where C_{tb} = towboat cost per ton-mile

c_{tb} = towboat cost per hour

T_1 = enroute transit time

n = maximum number of barges per tow

U_t = utilization of tow size

q = nominal barge capacity, tons

U_b = utilization of barge capacity

D = one way distance

E = fraction of empty movements

C_b = barge cost per ton-mile

c_b = barge cost per hour

C_c = cargo holding cost per ton-mile

c_c = cargo holding cost per hour

164. Cost for lockages is computed by replacing T_1, enroute transit time, with T_2.

$$T_2 = T_s + T_d \tag{25}$$

where T_s = lock service time

T_d = lock delay time

T_s and T_d are unique for each lock so that total lockage costs equal the sum of the individual lockage costs.

Existing Models To Compute Trip Delays

165. Each of the cost models presented above computes costs per ton-mile as a linear function of total transit time. One major component of total transit time is de'ay time at locks (i.e., time spent by a tow in a queue waiting to be sent through the lock). Lock delay time is one component of total lockage time, the other being lock service time. REMR policy exerts a clear influence on lock delay time through its effect on lock closures for inspection, routine maintenance, major rehabilitation, and emergency repair. Reviewing a sample of 25 locks, Hochstein, Patton, and Louis Berger and Associates (1981) revealed the following figures:

Total Downtime	419 days/year
Average Downtime	16.8 days/year/lock
Total REMR Downtime	265 days/year
Average REMR Downtime	10.25 days/year/lock

166. The average REMR downtime of 10.25 days per year is a significant amount of time for a lock to be out of service, but more important than the amount of downtime is its distribution and type. If most of the downtime results from routine maintenance and inspection scheduled during low traffic periods, then shippers' costs would be affected very little. However, if the downtime was due to emergency repairs during high traffic hours, the extra costs borne by shippers could be very high.

167. The other component that contributes to lock delay is lock service time (i.e., the time required to process a tow through the lock without delays). Ways that the level of REMR effort could affect lock service time will be discussed later.

168. The literature search found two models that account for the effect of lock downtime and service time on inland navigation. One model relates lock capacity to available lock time but does not deal explicitly with the delay experienced by a particular tow. Thus it does not quite agree with the cost models presented above. However, it is a possible method for evaluating the effects of REMR policies on the other functions of the waterway system such as military transportation. These other functions are not so easily quantified in dollars. The other model, which does apply to the methods of tallying costs reviewed earlier, is based on queuing theory and explicitly figures delay or queue length as a function of several parameters. The lock capacity model is discussed after the queuing model below.

Queuing model

169. Using queuing theory, DeSalvo conducts an analysis of delays encountered at individual locks. An arrival rate for tows, λ, is computed as

$$\lambda = \frac{A}{C} \tag{26}$$

where A = total tonnage to be carried on waterway segment

C = optimal (or average) tow size

170. In practice, λ could be determined empirically by actually counting the number of barges passing a particular point in some time period. λ could vary with the location, time of day, and season in the year. It is in the

that to deliver A tons at C tons per trip with p the percentage of unloaded barges, then the shipper must adjust λ such that

$$\lambda' = (1 + p)\,\lambda; \quad 0 <= p <= 1 \tag{27}$$

This presentation will continue to use the arrival rate λ as the actual arrival rate of tows and adjust tonnage figures as affected by empty barges in some other way.

171. If the assumption is made that the probability of a tow's presence at any given point on the waterway is independent of the elapsed time since the last tow was there, then a Poisson distribution applies. The probability that r arrivals occur within time t is expressed as:

$$P(t) = \frac{[(\lambda t)^r \exp(-\lambda t)]}{r!} \tag{28}$$

This probability distribution assumes random arrivals as implied above. The mean, or expected, arrival rate is λ so that in time t, an average of λt arrivals will occur at a given lock. The expected time between arrivals is $1/\lambda$.

172. The average delay per tow can be computed by using the queuing theory analysis approach. A standardized coding system is used to describe the major differences among numerous variations in the queuing system. This code is of the form A/B/m, where A and B are letter symbols and m is an integer constant. The letters A and B indicate the probability distribution of traffic interarrival times and of service times, respectively, and m is the number of identical parallel servers in the queuing system (thus, m can take values from 1 to infinity).

173. The standard code letters used for probability distributions (A and B) in queuing theory are:

M = Poisson (i.e., negative exponential probability distribution function for traffic interarrival times or for service times; M stands for memoryless)

D = deterministic (i.e., interarrival or service times are constant)

E_k = k^{th}-order Erlang distribution

E_k = k^{th}-order Erlang distribution

H_k = k^{th}-order hyperexponential distribution

G = general distribution (i.e., any distribution at all)

The coded systems also assume independence of successive traffic arrival times and of successive service times at the queuing system.

174. Other abbreviations are also used to indicate the most commonly encountered queue disciplines. FIFO is used to indicate the first-in, first-out queuing arrangement, also known as FCFS (first come, first served). Similarly, LIFO (last in, first out) or LCFS (last come, first served) indicate the situation in which the last traffic to join the queue becomes the next in line for entering service. The abbreviation SIRO may be used to indicate service in random order.

175. Lave and DeSalvo (1976) treat the components of lock service time as random variables such that the service rate also has a Poisson distribution with a mean of μ. $1/\mu$ represents the time required to service one arrival and can be measured empirically for each lock or class of locks. Under these assumptions, the system is called M/M/1 queue (simple single-server queuing model) and results in the derivation of the following equations:

$$T_L = \frac{1}{(\mu-\lambda)} \tag{29}$$

$$T_{Lq} = \frac{\lambda}{\mu(\mu-\lambda)} \tag{30}$$

where T_L = expected total locking time

T_{Lq} = the waiting time in the queue

These equations are easily verified if one recalls that expected service time $T_s = 1/\mu$, so that:

$$T_{Lq} + T_s = T_L; \quad \frac{\lambda}{\mu(\mu-\lambda)} + \frac{1}{\mu} = \frac{(\lambda + \mu - \lambda)}{\mu(\mu-\lambda)} = \frac{1}{(\mu-\lambda)} \tag{31}$$

As μ approaches λ , T_L and T_{Lq} approach ∞.

176. Consider μ in terms of λ, such that

$$\mu = n\lambda, \ n >= 1 \tag{32}$$

then

$$T_L = \frac{1}{[(n - 1)\ \lambda]} \tag{33}$$

and

$$T_{Lq} = \frac{1}{[n(n - 1)\ \lambda]} \tag{34}$$

177. Figures 31 and 32 allow us to see how T_L and T_{Lq} vary with n. If n = 2, that is, if the service rate is twice the arrival rate (and the service time is one-half the time between arrivals), then the total expected locking time T_L is $1/\lambda$, the time between arrivals, and the time in queue is $1/2\ \lambda$, half the total waiting time. If n < 2, then total time in service, T_L, and time in queue, T_{Lq}, both rise dramatically. This is especially true for T_{Lq}. If small increases in service rate can be effected by changes in REMR policy, then substantial savings in shipping times could result, especially if

$$\lambda <= \mu <= 2\ \lambda$$

178. A cost model that showed the marginal effects on the service time would be a very effective REMR management tool. The model would allow the comparison of marginal costs of service time reduction with the marginal benefits of reduced waiting time. To check whether this theory and its assumptions apply to real life situations on the waterway system DeSalvo obtained data for five locks on the Illinois Waterway for the years 1949 and 1950. Locking operations were being studied intensively as part of an economic analysis of constructing larger locks. Table 14 shows that predicted total waiting times and times in queue matched reasonably well with actual reported times.

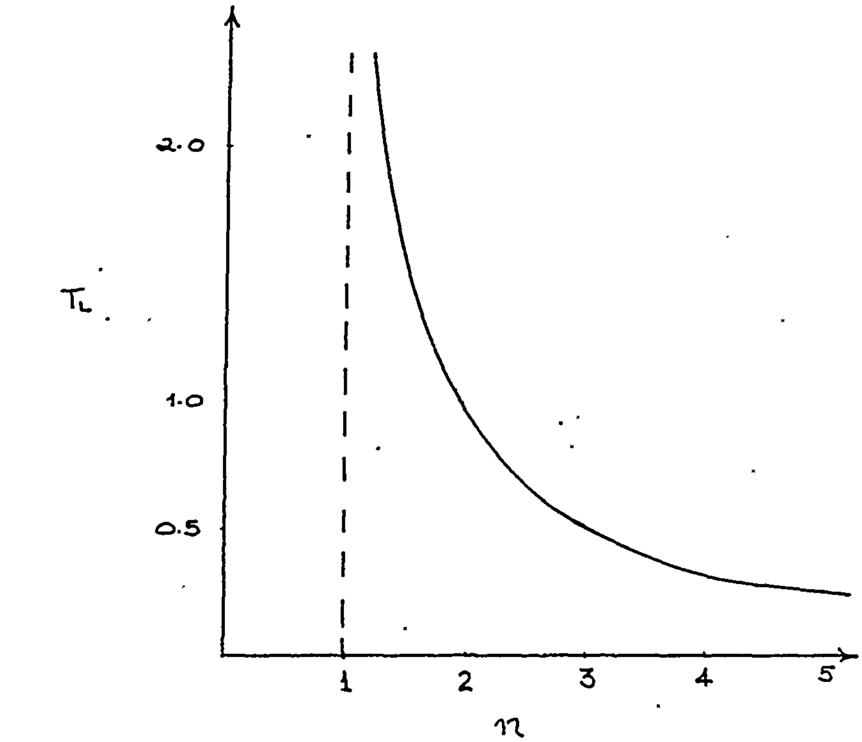


Figure 31. Expected time in service

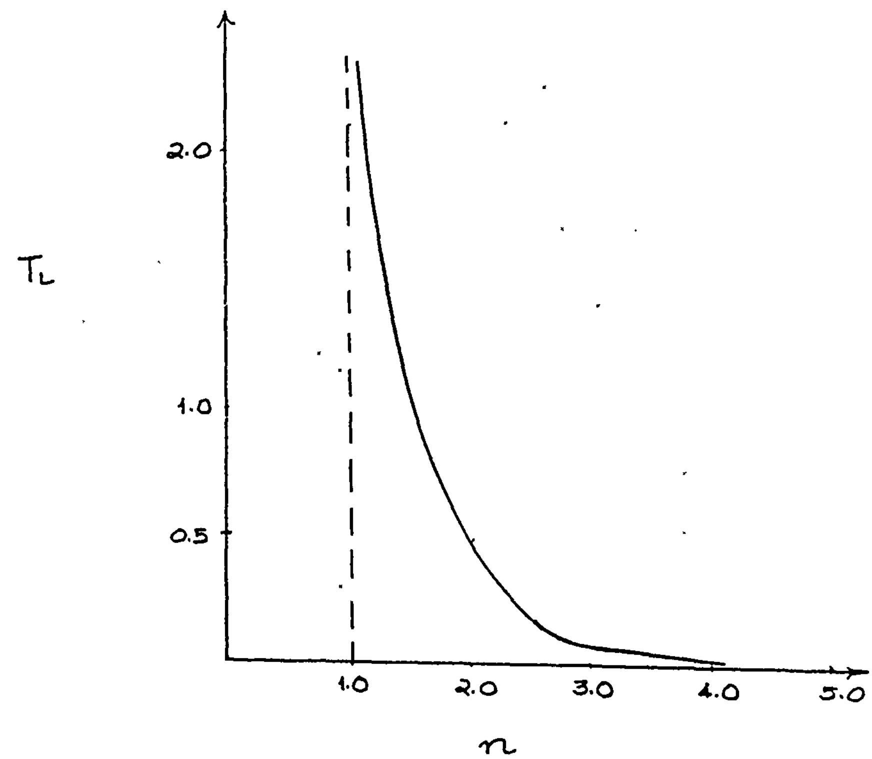


Figure 32. Expected waiting time

Table 14

Average Locking Time in Minutes per Tow for Five Locks on the Illinois Waterway, 1949

Lock	Predicted Total Waiting Time	Reported Total Waiting Time	Predicted Time In Queue	Reported Time In Queue
Lockport	75.9	68.4	22.8	15.3
Brandon Road	89.5	75.8	30.2	16.5
Dresden Is.	57.7	55.5	14.3	12.1
Marseilles	70.6	64.2	20.1	13.7
Starved Rock	47.6	50.1	10.1	12.6

Source: Interim Survey Report: Duplicate Locks, Illinois Waterway

179. Wilson (1978) showed, however, that the M/M/1 model does a poor job of predicting delays. He proposed an M/G/1 and M/M/2 queuing model for predicting delays at locks and claimed that the model fit the simulation results. Glassey and Ross (1976) also pointed out that the mean waiting times predicted by the M/G/1 model differed significantly from observed waiting times. They proposed a limited queue length M/G/1 model for one-chamber and an M/G/1 model with random batch size for two-chamber locks. They have not provided any numerical results for comparison.

180. Another result of queuing theory is a formula relating waiting time as a function of lock capacity and actual lock traffic. Both the NWS and the TCM represent average tow delay time at a lock as follows:

$$D = \frac{(k * t)}{(Q - t)} \tag{35}$$

where D = delay time at lock

k = lock delay parameter

t = traffic at lock, tonnage per time

Q = lock capacity, tonnage per time

181. In the NWS model, both capacity Q and ock delay parameter k are calculated by a computer model known as LOKCAP. The lock delay parameter is a function of service time and the standard deviations of service times at a lock. Figure 33 shows that the delay versus traffic plot has the same hyperbolic curve as delay versus service time in the DeSalvo model except that it is flipped about the vertical axis. This similarity can be demonstrated mathematically as follows:

$$\text{Capacity } Q = \left(\frac{1}{T}\right) L \tag{36}$$

where T = service time = $1/\mu$

L = tonnage/tow

so that

$$Q = \mu L \tag{37}$$

$$\text{traffic } t = \lambda L \tag{38}$$

then

$$D = \frac{(k\ t)}{(Q - t)} = \frac{(k\ \lambda\ L)}{(\mu - \lambda)\ L} = \frac{(k\ \lambda)}{(\mu - \lambda)} \tag{39}$$

But the TCM asserts that k is just the delay when traffic t = 1/2 Q. From DeSalvo's model:

$$T_L = \frac{1}{(\mu - \lambda)} \tag{40}$$

$$T_L \Big| = \frac{1}{\lambda} \tag{41}$$

$$\mu = 2\lambda$$

hence

$$\text{delay } D = \left(\frac{1}{\lambda}\right) \frac{\lambda}{(\mu - \lambda)} = T_L \tag{42}$$

Thus the two models are essentially the same.

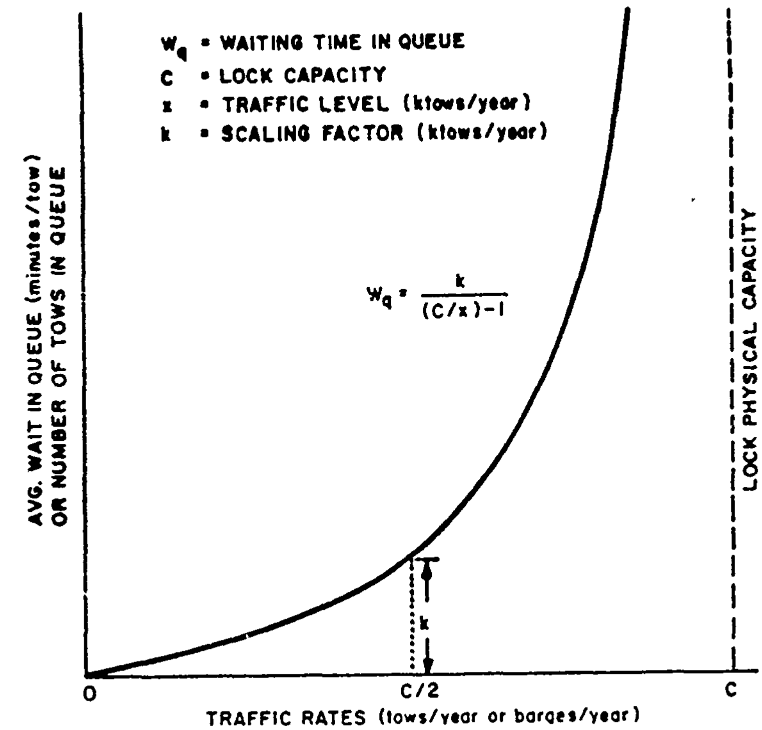


Figure 33. Typical lock traffic-delay curve

Lock capacity model

182. The NWS (1983) derives an equation relating lock capacity to a number of variables:

$$Q = \left(\frac{1}{T}\right) N\ L\ S \prod_{i=1}^{4} k_i \qquad (43)$$

where Q = yearly capacity in tons

T = average service time

N = number of minutes per year

L = average tonnage per barge

S = average tow size (barges per tow)

$k_1 = 1-a_1$, where a_1 is frequency of empty barges

$k_2 = 1-a_2$, where a_2 is frequency of downtime

$k3 = 1-a_3$, where a_3 is seasonality factor

$k_4 = 1-a_4$, where a_4 is percentage of time used for recreation

Service time for a lock, T, is computed as

$$T = A_f + E + F + X_f + P_d(A_t + E + X_t + 2F + D) + (P_s S) \tag{44}$$

where A_f = fly/exchange approach time*

E = entry time

F = chambering time

X_f = fly/exchange exit time

P_d = frequency of double lockages

A_t = turnback approach time**

X_t = turnback exit time

S = extra time for setover lockages‡

D = extra time for double lockages‡‡

P_s = frequency of setover lockages

S = average tow size (barge per tow)

183. Capacity, as defined by the NWS Equation 44 is a linear function of downtime, whose frequency is represented by a_2. Since there is no clear relation between shipper's costs and the tonnage capacity of a lock, the capacity model is ill suited for use in this economic analysis. However, it could be of use in determining REMR impacts in other areas. For instance, in a national emergency and under conditions of centralized scheduling, the lock capacity could serve as a useful indicator of the upper bound of traffic a lock could pass if optimally scheduled.

---

* A fly approach/exit is executed when the lock has been idle and the vessel proceeds directly into/out of the chamber. An exchange approach/exit is executed when inbound and outbound vessels pass each other.

** A turnback approach/exit is executed during a lockage when no vessels are served. A turnback is a reversal of water level in a lock chamber with no vessels in the chamber.

‡ A setover lockage is one "in which the towboat and one or more barges are separated as a unit from the remaining barges and set alongside them in the lock chamber."

‡‡ A double lockage is one in which the two passes through in two segments or "cuts."

184. It is worth noting that REMR activities have an impact on another parameter in the capacity equation, the average service time (see Equation 44). As seen earlier, service time also plays a vital role in determining lockage and waiting times for barges. REMR policy can affect service time in a number of ways. The condition of lock valves and lock gates influences chamber filling and emptying time. Approach and exit times depend on the maintenance of channel depth and width through dredging. Other operational aspects of the lock may depend on the level of maintenance performed. Any reduction in service time or waiting time resulting from improved REMR performance leads to a reduction in shipping cost that can be computed from the cost models reviewed above.

Relation between downtime and queuing

185. So far, delay time has been considered a function of lock service time. How does lock downtime connect to queuing theory analysis of delay? If a lock shuts down and traffic continues to flow at other points in the system, the queue at the closed lock grows at the rate of λ tows per period. The effect of lock closures on tow delays was investigated in a computer simulation by Stanley Consultants (Antle, Sharp, and Goiocoechea 1981) in connection with rehabilitation proposals for Lock and Dam 26 on the Mississippi River. Appendix B describes the basis for the model and the results of several simulation runs and is included in its entirety as an example of the application of queuing theory to lock closure delay.

Other Aspects of Cost Reductions

Reliability

186. The reliability of the inland waterways network is a major influence on shipper's perceived costs when it is important for the shipper to accurately target an arrival time. Although queuing analysis provides expected travel times and expected delays in the sense of the statistical mean, in some cases the value of the mean may be less important than the variance (or its square root, the standard deviation) about the mean. Consider an example where a shipment must get to its destination by time T^*. Figure 34 shows two probability distributions for arrival times corresponding to two different hypothetical maintenance policies. Policy 1 results in an expected time of

travel of T_1 with a standard deviation of s_1. Policy 2 is associated with a smaller expected travel time, due to a lower frequency of lock closures for inspection, routine maintenance, and nonemergency repair. Its standard deviation s_2 is larger than s_1, due to a higher frequency of emergency closings of long duration. The higher standard deviation of Policy 2 leads to a greater uncertainty in actual travel time. By comparing the areas under the probability curves, one can see that:

$$P(T_1 \leq T^*) < P(T_2 \leq T^*) \text{ even though } E(T_1) > E(T_2) \qquad (45)$$

where E(T) = the expected value, or mean, of T.

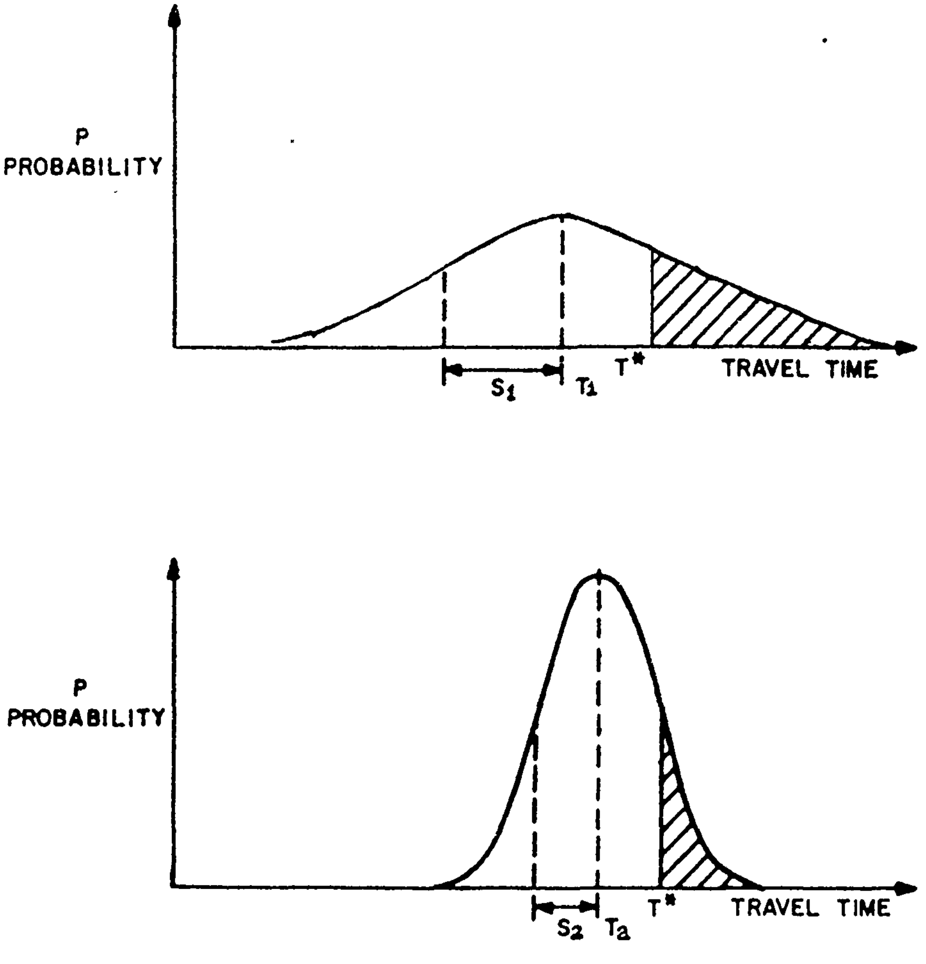


Figure 34. Distributions of travel times as a function of maintenance policies

187. The shipper who requires a certain level of reliability in the travel time of a particular commodity could suffer economic loss as a result of uncertainty in predicting arrival time of that commodity. Conversely, a reduction in uncertainty would result in a reduction of shipping costs. Inadequate reliability could lead the shipper to an alternate transportation mode. These are some of the potential impacts that REMR policy could have on shippers' costs through its effect on reliability. However, a search of Corps-related literature uncovered no model that links reliability of a waterway segment to frequency of lock closures or other stochastic processes (e.g., accident frequency).

Cost reductions because larger or longer tows can use the waterway (e.g., by channel straightening or widening)

188. Channel maintenance through dredging affects the width and depth of the waterway, and the radius of curvature of bends in the channels. Constricted channels increase tow costs by increasing the number of maneuvering operations a tow must undertake and by increasing delay time when a tow moving in one direction must yield to another moving in the opposite direction. A literature search uncovered no statistics or models dealing with increases in tow costs or tow delays due to constricted channels.

Cost reductions by permitting barges to be more fully loaded (e.g., by channel deepening)

189. Channel deepening decreases tow costs in two ways:

a. Increased depth allows for increased draft and so increased load. If bottom clearance is held constant as channel depth increases, then barge load is a linear function of channel depth. Increased load per barge allows either the use of fewer barges to transport the same amount of material (hence a cost reduction) or the use of the same number of barges to transport more material (hence a profit increase).

b. For a given load, increased channel depth increases the speed a tow can achieve by reducing bottom turbulence and other drag effects. Howe et al. (1969) have shown that resistance of a barge flotilla can be represented by the following expression:

$$R = 0.07289 \exp\left(\frac{1.46}{(D - H)}\right) S^2 H^{0.6} \left(\frac{50}{(W - B)}\right) L^{0.38} B^{1.19} \qquad (46)$$

where R = resistance

D = depth of waterway, in feet

H = draft of barge flotilla, in feet

S = speed of tow in mph (still water)

L = length of barge flotilla, in feet

B = breadth of barge flotilla, in feet

W = width of waterway, in feet

190. (D - H) is the bottom clearance of the tow. For a given load, hence a given draft, and a given resistance (balanced by EP, effective push), speed increases according to $\exp(-[1.46/(D - H)])$. For large values of clearance, (D - H) > 5 ft, increases in clearance do not add appreciably to resulting speed. For (D - H) < 5 ft, increases in speed gained by increasing (D - H) can be substantial.

Transport Benefits Other Than Cost Reductions

Shift in mode

191. The WRC manual (1985) states:

> For traffic that would use a waterway with the project but uses a different mode, including a different waterway without the project, the benefit is the difference between the costs of using the alternative mode without the project and the costs of using the waterway with the alternatives under consideration.

192. Interpreting the word "project" as "REMR activity" would make this evaluation criterion applicable to shift in mode benefits derived from improved REMR practices. Cost reduction benefits resulting from changes in REMR policy can be compared to differential costs of alternative transport modes. If cost reductions lower waterway transport costs for a particular commodity below the costs of current alternative transport modes, there will be an incentive for shippers to shift from the current mode to the waterway. The increase in traffic from this shift may significantly increase delay costs at locks and other constructions. This effect will have to be evaluated to determine whether total transport costs on the waterway remain lower than those of the alternative mode.

Shift of origin-destination benefit

193. The WRC manual (1985) states:

> If a project would result in a shift in the origin of a commodity, the benefit is the difference in total costs of getting the commodity to its place of use with and without the project.

194. Amending this passage to read "change in REMR policy" where it now reads "project" would make this evaluation criterion applicable to shift of

origin-destination benefits resulting from changes in levels of evaluation, repairs, or rehabilitation.

New movement benefits

195. The WRC manual (1985) states:

> This benefit applies if a commodity or additional quantities of a commodity would be transported only because of lowered transportation charge with the project.

196. Again, substituting "change in REMR policy" for "project" results in a criterion for evaluating the benefits of new commodity movement due to REMR-related actions.

Accomplishing the Army's mission

197. The Digest of Water Resources Policies and Authorities (CE 1983) summarizes the national defense and emergency policies of the Corps of Engineers as follows:

> Mobilization. The Corps of Engineers is one component of the United States Army team. The Congress, by assigning the Chief of Engineers national missions of civil works for water resources development in addition to the military missions, has provided the nation a vital element of insurance for the rapid mobilization and discharge of military engineering, construction and logistic services in time of emergency. The Civil Works program and the peacetime military construction program provide the base for maintenance of a well rounded organization providing engineering, construction and logistic services to the Army. In times of emergency those Civil Works projects not essential to National defense will be rapidly curtailed to provide an immediate working staff to execute military engineering work. Inasmuch as all phases of rapid mobilization depend on rapid construction, appropriate elements of the Corps of Engineers maintain plans for mobilization. The Civil Works program is accomplished in a manner which enhances this mobilization capacity.

198. Mobilization capability depends in part on the capacity of the waterways system to deploy military equipment and supplies, either to military units stationed domestically or overseas, or to "a theatre of operations during hostilities." The capacity of the waterways system is generally limited by the capacity of the navigational locks. Lock capacity is a function of lock size, lock service time, and lock downtime. REMR policy affects only service time and downtime. If specific defense requirements for the movement of equipment and supplies in terms of tonnage or number of barges per unit time are provided, then the Corps (or its contractors) could determine a REMR policy that helps satisfy these requirements (based, for example, on the

capacity analysis described earlier). Alternative REMR policies • ;.?.acetime and wartime could be identified assuming that deployment requirement· 'u'ı ı. differ.

199. Other aspects of national defense relevant to the waterways . stem are as follows:

a. Support of the economies of allied nations in time of war.

b. Ac 'ss to Naval facilities and to facilities which support the US ..avy Fleet.

c. Movement of missile and rocket components for NASA.

d. Movement of strategic materials.

200. The same analytical techniques and mathematical models that apply to regular commercial navigation would apply to the water transport issues above. The basic question remains: How does maintenance affect the rate of movement of water traffic? The difference between assessing defense-related impacts and commercial impacts lies in the relative ease of placing a dollar figure on the commercial impacts. It may be more difficult to balance REMR costs against attendant defense-related benefits without an economic criterion for evaluating those benefits.

Impacts of maintenance on safety

201. Two major questions need to be considered in assessing the relationship between REMR policy and waterways safety: What effect will different REMR policies have on waterway safety and how do accident rates affect the level of REMR expenditures? The cause-effect connection works both ways. Since this report is concerned with consequences of REMR policy, the discussion is limited to effects of REMR activities on safety.

202. The major goal of a safety policy is a reduction in accidents that result in property damage, personal injury, or death. The NWS (1983) identifies four types of vessel casualties of major concern:

a. Collisions of moving vessels.

b. Rammings (collision of vessel with fixed object or moored vessel).

c. Groundings.

d. Cargo fires and/or explosions.

203. Vessel control accidents have been found to occur most frequently on those segments of the waterways with one or more of the following

characteristics (Miller and Kearney, Inc. 1981):

a. Bends.

b. Channel intersections.

c. Locks.

d. Narrow channels.

e. High traffic levels.

204. Miller and Kearney, Inc. (1981) cited four potential strategies for reducing waterways accidents that were developed by a private consulting firm contracted by the US Coast Guard.

a. Personnel training and licensing.

b. Structural improvements to waterways system.

c. Alteration of operating procedures.

d. Improvement to vessels.

Only strategy b relates to REMR practices. Many of the programs proposed to increase waterway safety are identical to those proposed to decrease shippers' costs.

Channel maintenance

205. Many groundings occur at channel bends, crossings, or intersections. Shoaling in these areas could be reduced by increasing dredging frequency or increasing channel depth and width. Inadequate approach channels to bridges and locks contribute to high accident rates at these structures, again suggesting that maintaining channel depth and width would be an appropriate strategy to reduce the accident rate.

Submerged objects

206. Submerged wrecks, snags, old bridge piers, and shoals provide a hazard to vessels on the waterways. "Legal responsibility for marking and clearing wrecks lies with the vessel owner, but if the owner cannot or will not do so, the Coast Guard can mark it and the Corps can remove the wreck at their discretion (later billing the owner for the costs)" (Miller and Kearney, Inc. 1981).

207. Determining the cost effectiveness of channel maintenance as it affects accident rates would be the most plausible direction for further research. Because dredging and river training programs are expensive, it is necessary to establish a connection between a dollar spent on these programs and the safety benefits derived due to reduced accident losses. Safety

benefits would be one component in a comprehensive cost-benefit analysis of a REMR program.

Other Benefits to National Economic Development

208. The focus of this report has been on the effects of REMR on navigation, particularly (in these early stages of research) as influenced by locks. However, it is conceivable that REMR policies would generate benefits in other economic sectors as this work is extended to other facilities. Such benefits would also fall within the conceptual framework proposed in Part II, and are summarized below.

Water supply

209. The WRC manual (1985) establishes the following economic principle for the economic evaluation of water supply:

> The conceptual basis for evaluating the benefits from municipal and industrial water supply is society's willingness to pay for the increase in the value of goods and services attributable to the water supply.

210. Those Corps owned or maintained facilities that could conceivably affect the municipal and industrial water supply are:

a. Dams, levees, dikes, and other water impounding facilities.

b. Canals, channels, pipes, and other water conveyance facilities.

c. Gates, wickets, weirs, and other flow-control mechanisms.

211. Those areas of water management that would be sensitive to REMR policy would be:

a. Water supply (water available to a region or community).

b. Water quality.

The marginal benefits gained or lost due to the effect of a particular REMR policy on the water supply would have to be measured against the marginal cost of that policy compared to some baseline policy.

Flood, erosion, and sedimentation control

212. The WRC manual's benefit evaluation procedure identifies three economic problems associated with water and the use of land and water resources in agricultural production:

a. The cost of damage to crops, pasture, and range by water inundation, drought, sedimentation, and erosion.

b. Costs associated with using water and land resources that are subject to variation with the application of various water management practices or the installation of water control measures. For example, future conditions without the project result in poor soil drainage situations that may require more cultivation and more horsepower.

c. Impaired productivity or use of land resources.

213. The NED benefit of water management practices or water control measures is the reduction in the economic significance of the three problems listed above. A preliminary literature search yielded the following list of potential areas of maintenance impact:

214. Dam and levee maintenance. Design standards for dams require a minimum freeboard (height of wall above reservoir level) for given reservoir conditions (e.g., surface area of reservoir, wind conditions, fetch, etc.). If this freeboard is compromised by superficial erosion of earthen dams or levees or by superficial deterioration of a concrete facility, the risk of inundation is increased. Of course, more serious structural deterioration which increases the likelihood of total failure (as opposed to overtopping only) must also be prevented.

215. Spillway maintenance. Both gated and nongated spillways must be able to accommodate design flows. According to an English manual of reservoir safety, "Where a gated spillway is employed, high standards of maintenance are required and regular operation essential" (Institute of Civil Engineering 1978). Design criteria suggested by this manual require that the capacity of the spillway exceed the amount calculated by the following:

$$[(\mathrm{RSMD}/20)\ (0.15\mathrm{m/s})] \text{ per km of catchment area} \tag{47}$$

where RSMD is a geographically based index of flood producing rainfall. Spillways and spillway gates should be designed and maintained such that debris and ice do not clog them. Any REMR policy that affects the capacity of the spillway or the operation of the gates will also affect the risk of dam overtopping or some other form of inundation (e.g., spillway overtopping).

216. Channel maintenance. The hydraulic stability or capacity of a waterway is increased by channeling and paving. A policy for channel and channel pavement maintenance directly influences the ability of a river to withstand heavy rainfall without flooding.

Agricultural drainage and irrigation

217. The Corps of Engineers is not directly involved in irrigation or drainage projects, which are generally built and operated by individual enterprises, district organizations, the Bureau of Reclamation, commercial organizations, and state, city, or town organizations (Framji and Mahajan 1969).

218. The Corps' role in irrigation is to provide an adequate water supply through dam and reservoir systems. In drainage areas, the Corps must maintain levees or other walls that impound water and make available land which would otherwise be unusable.

Hydropower benefits

219. The Corps of Engineers is the nation's largest builder and operator of hydroelectric facilities. As of 1 January 1980, the Corps reported a total of 75 power plants with a nominal capacity of 18,367 MW, more than half the generating capacity of all existing Federal hydroelectric plants. A comprehensive REMR management program for the Corps would have to consider the life-cycle needs of this sizeable enterprise. This report concentrates on inland navigation issues and covers a specific facility class in some depth. A thorough coverage of all the REMR issues associated with power plants is beyond the scope of this report; however, a brief outline of the issues is in order.

220. A preliminary literature search revealed that the current approach to power plant maintenance is almost exclusively centered on the inspection, maintenance, and repair of manufactured components of the plant. Schedules and procedures for inspecting and maintaining pipes, valves, turbines, and other components are suggested by the manufacturers. No literature was found that discussed the maintenance of the power plant overall as a constructed facility, or that addressed problems peculiar to hydroelectric plants, such issues as concrete and steel deterioration.

221. Hydropower engineering has traditionally used several design factors which can be related to possible REMR impacts on power production. The capacity factor, CF, is the average ratio of plant output to plant capacity as follows:

$$CF = \frac{PO}{PC} \tag{48}$$

where PO = mean power flow (gal/sec) * mean net head(ft)

PC = discharge capacity of turbines (gal/sec) * mean net head

222. Any REMR practices that influence the amount of water in the pond or reservoir available for power production would also influence the capacity factor and hence the relative intensity of power plant use. For instance, poorly sealed spillway gates might result in water lost to power production. Power output is a function of the mean net head that also could be reduced through spillway losses.

223. The pondage factor, PF, is a multiplier that is the ratio of the time that water is ponded to the time that water flows through the plant. The higher the pondage factor, the larger the reserve volume of water and the larger the head. Again, water lost through poorly maintained spillway gates or other leaks decreases the pondage factor, the net head, and the plant output.

Benefits derived from recreation

224. The WRC benefit evaluation procedure establishes the following criterion for assessing recreation benefits:

> Benefits arising from recreation opportunities created by a project are measured in terms of willingness to pay for each increment of supply provided.

225. Three methods of recreation benefit evaluation are presented:

a. The Travel Cost Method.

b. The Contingent Value Method.

c. The Unit Day Value Method.

226. Travel Cost Method. The basic premise of the Travel Cost Method is that per capita use of a recreation site will decrease as out of pocket and time costs of traveling to the site increase, other variables being constant. This method of determining recreation benefits is clearly compatible with the lock delay models presented in connection with commercial navigation. A lock REMR policy that affects lock service time or downtime will also affect the time costs of recreational travel.

227. Contingent Valuation Method. The contingent valuation method estimates NED benefits by directly asking individual households their willingness to pay for changes in recreation opportunities at a given site.

Individual values may be aggregated by summing willingness to pay for all users in the study area.

228. An extensive survey of households is justified when comparing recreational opportunities with and without a water resources project. It becomes more difficult to justify this kind of survey for changes in recreational opportunities resulting from alternative REMR policies. If a proposed change in REMR practice is suspected to have a significant impact on recreational opportunities, this evaluation method would be appropriate.

229. Unit Day Value Method. The unit day value method relies on expert or informed opinion and judgment to estimate the recreation user's average willingness to pay. This method allows the cost of a change in REMR policy affecting recreational use to be compared to an expert or informed judgment of the value of the change in recreational capacity.

Physical impacts of maintenance

230. In trying to determine the relative impacts of different REMR policies, it would help to know what happens if no maintenance is performed. A no maintenance scenario corresponds to the "without project" base case of the WRC benefit evaluation procedure against which project costs and benefits are measured. It may not be desirable to use the no maintenance case as the base case since some level of REMR effort can be presumed. However, the no maintenance condition can be presented as the worst case in the spectrum of REMR policies and thus serve as a basis of comparison in this light.

231. Antle, Sharp, and Goiocoechea (1981) have devised a suggested format for cause-effect relationships at locks and dams (Table 15). A complete tabular description of the physical effects of accidents and deterioration provides a framework and starting point for investigating the impacts of alternative REMR practices and policies. Similar relationships could be identified for other Corps facilities.

Development of Consequence Models for Lock REMR Activities

232. In Part II the framework for managing REMR activities throughout a network of locks was presented. Analyses to determine needs, evaluate alternatives, estimate costs and benefits, and assess priorities require

Table 15

Suggested Format for Cause-Effect Relationships

Component and Cause	Effect
• **Regulating Weir**	
1. Weathering of face and top concrete surfaces (freeze and thaw)	Loss of pool
2. Deterioration of butterfly valves (corrosion and wear)	Inability to regulate pool level
• **Lock Walls**	
1. Spalling and abrading of lock walls (freeze-thaw)	Increased frequency of deterioration leading to failure
2. Walking surface spalling (above lockwall)	Safety hazard worsens with time
3. Cracking of lockwall at recess areas	Further propagation leading to failure
• **Lower Guidewall**	
1. Sheetpipe wall sections are corroded, overstressed, and anchored too high. Check posts failing	Moving riverward creating obstacles to navigation. Will eventually fail
2. Wood fenders splintering and frequently damaged	Require frequent replacement. High maintenance cost
3. Downstream endwall damaged often by tows. Not of sufficient strength nor bumpered	Further damage leading to more extensive failures and more costly repairs
• **Upper Guidewall**	
1. Wall sections experiencing differential settlement. Sheetpipe sections are corroded and overstressed	Moving riverward creating hazard to navigation and safety hazard on top along sidewalk
2. US endwall frequently damaged by tows	Further damage leads to more extensive repairs

(Continued)

Table 15 (Concluded)

Component and Cause	Effect
• Lock Equipment Components	
1. Quoin end seals, interseals	Winter ice buildup slows lock operation
2. Open grating over machine pits	Ice and snow hinders operation of lock machinery
3. Wear of all lock machinery	Failure causes long downtime for replacement parts
4. Pitted piston arms (miter gate)	Excessive maintenance costs. Repacking seals and loss of hydraulic fluid
5. Corroded black steel tainter valve and hydraulic cylinder lines leak more frequently	Difficult to locate leaks. Long downtime for repair
6. Difficult to manually operate hydraulic valves to open and shut intergates	May fail to move and cause downtime
7. Tainter valve seals leak	Could fail
8. Tainter valves are corroded	Could fail
9. Cannot easily reverse operation of tainter valves	
• Wicket Dam Components	
1. Worn herters	Wickets will not stand up or are difficult to put in place. May lose pool levels
2. Worn Sius	Poor support for wickets
3. Damaged and worn baffle locks	D.S. scour below apron
4. Damaged apron	Herters not well supported in concrete
5. Wickets unsafe to raise and lower	Winter ice passage dangerous. Possible loss of life and equip.

predictions of the life-cycle agency and user costs (benefits and disbenefits) associated with each lock REMR policy alternative. The procedures to compute agency costs were described in Part III, while the user benefits due to lock REMR activities have been quantified in Sections 4.1 through 4.5. More general economic benefits of REMR actions were discussed in Section 4.6. However, because these benefits are difficult to relate to locks specifically, they will not be addressed below.

233. In general, REMR activities performed on locks may result in reduced shipping costs to users, although scheduled downtime may increase. Components of user costs relevant to REMR performance are delay cost, downtime cost, traffic mode diversion cost, and safety and reliability cost.

234. The existing models to compute delay costs and downtime costs were described earlier. These models do not take into account the interdependencies, or network effects, between succeeding locks. The traffic mode diversion cost and safety and reliability cost models have also been described. Traffic mode diversion costs are now computed for capital construction only. At a reasonable range of facility condition, the effect of a REMR activity would be some improvement in the performance of an existing lock, although the effect on traffic mode diversion would be very insignificant. Therefore, the user benefits associated with traffic mode diversion will not be considered here. The safety-related benefits of lock REMR to the user is a controversial issue since there are no uniform and standard procedures to compute them. The costs or benefits of trip reliability are theoretically straightforward to compute, but require models and data that stratify commodity flows in a way much more detailed than that contemplated for REMR management. Therefore, safety and reliability costs and benefits will also not be considered further.

235. To compute the consequences of a lock REMR activity one needs to compute the changes in total transit time, which is the sum of time required to travel distance D at full or line-haul speed (T_f), locking time (T_L), make-tow time (T_m), break-tow time (T_b), and miscellaneous delay time (T_o). The locking time and delay time are the major time parameters affected by a lock REMR activity. Therefore, for the purposes of computing the reduction in delay costs due to lock REMR, only the changes in locking time (T_L) and delay time (T_o) will be considered. Procedures to compute delay costs and downtime costs are described below.

Delay cost

236. Delay costs are the costs incurred by the lock user or barge owner due to waiting delay and service delay at a lock. All the locks have limited capacity. When a tow is being serviced at a lock, other tows arriving at the lock will have to queue. The cost associated with that kind of delay is called delay cost.

237. The average tow delay at a lock is a function of the average service rate of the lock (μ), the standard deviation of the service time at the lock (σ), and the average traffic arrival rate at the lock (λ). The lock's service rate is the average number of average size tows that can be serviced in a given unit of time. The standard deviation of the lock's service time is the degree of variation in service time at the lock. As the lock is used more and more, the different components of the lock deteriorate or wear out. As a result, one expects the service rate to decrease and the standard deviation of service time to increase. How fast the service rate decreases or the standard deviation of service time increases depends on a number of factors including the rate of usage and wear, environmental influences on lock deterioration, and degree of aging.

238. As discussed in Part III, the condition of lock gates is described by the expected value of the lock gate condition index (GCI) and the standard deviation of the lock gate condition index (σ_{GCI}). The expected value of lock walls is described by the expected value of the lock wall condition index (WCI) and the standard deviation of the lock wall condition index (σ_{WCI}). The condition of mechanical equipment is described by the parameter Mfail, the probability of mechanical equipment failure. Since the service rate of a lock is a function of the lock condition, the service rate is modeled as a function of the expected value of the GCI, WCI, and the mechanical equipment probability of failure (Mfail):

$$\mu = f\ (GCI, WCI, Mfail) \tag{49}$$

239. Once the variables that affect the service rate (μ) are identified, the next step is to identify the actual functional relationship. One way to identify the functional relationship is through regression analyses. Time series data for a set of dependent and independent variables are needed

for these analyses (Ben-Akiva and Lerman 1985). However, since there are no historical data on GCI, WCI, and Mfail, regression techniques cannot be used to produce the desired functional relationship.

240. An idea of the likely form of this relationship can be obtained, however, by considering the known behavioral characteristics of the problem. For example, if the gate-wall condition index goes to zero, assuming other variables remain constant, the service rate should also go to zero. If the condition index goes to 10, meaning the gates and walls are in the best possible condition, the service rate should go to the maximum (the capacity). Similarly, if the mechanical equipment probability of failure goes to zero, assuming the other variables remain constant, the service rate should approach its maximum. And if the mechanical equipment probability of failure goes to 1, meaning the mechanical equipment could fail any moment, the service rate should drop to zero. Therefore, the service rate versus GCI, WCI, and Mfail relationships function should capture the behavior described above. A logistic function (or S-shaped function) satisfies the kind of behavior described above. The actual function is given by:

$$\mu[t] = \mu_0 \frac{\exp[a_3*(\mathrm{Mfail}[t]-0.50)]}{\{1+\exp[a_3*(\mathrm{Mfail}[t]-0.50)]\}}$$

$$* \frac{1}{\{1+\exp[b_3*(\mathrm{GCI}[t] - 5.0)]\} * \{1+\exp[c_3 * (\mathrm{WCI}[t] - 5.0)]\}} \qquad (50)$$

where $\mu[t]$ = service rate of the lock in year t

μ_0 = service rate of the lock in year 0

a_3, b_3, c_3 = coefficients

Mfail[t] = mechanical equipment probability of failure in year t

GCI[t] = lock gate condition index in year t

WCI[t] = lock wall condition index in year t

241. The shape of the relationship curve between service rate and the gate-wall condition index is shown in Figure 35. The relationship curve between service rate and the mechanical equipment probability of failure is

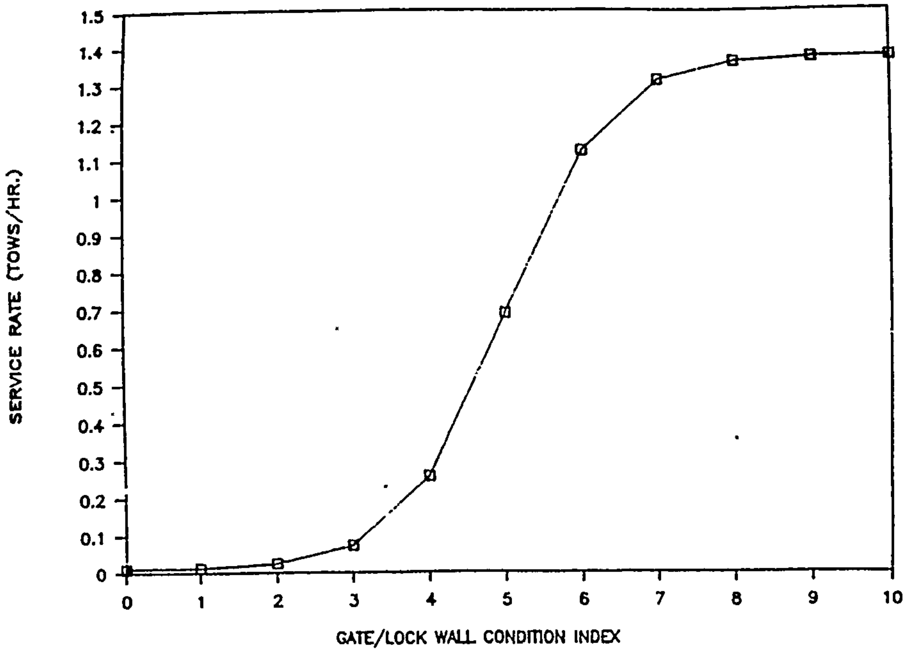


Figure 35. Relationship between service rate and gate-wall condition index

shown in Figure 36. The inflection point in Figure 35 occurs when the condition index is 5 and in Figure 36 when the probability of failure is 0.5.

242. Similarly, the standard deviation of service time distribution (σ) is a function of the lock gate condition index standard deviation (σ_{GCI}), the lock wall condition index standard deviation (σ_{WCI}), and the mechanical equipment probability of failure (Mfail):

$$\sigma = f\ (\sigma_{GCI},\ \sigma_{WCI},\ \mathrm{Mfail}) \tag{51}$$

243. To identify the functional relationship between σ, σ_{GCI}, σ_{WCI}, and Mfail, one needs to understand the effect that a change in an independent will have on the dependent variable, assuming the other independent variable values remain constant. For example, if the standard deviation of the condition index increases, the standard deviation of service time should also increase. Similarly, if Mfail increases, then should also increase. In other words, the standard deviation of service time is a composite effect of the standard deviation of the condition index and the probability of failure of mechanical equipment. And, in statistics, a composite variance of a system is simply

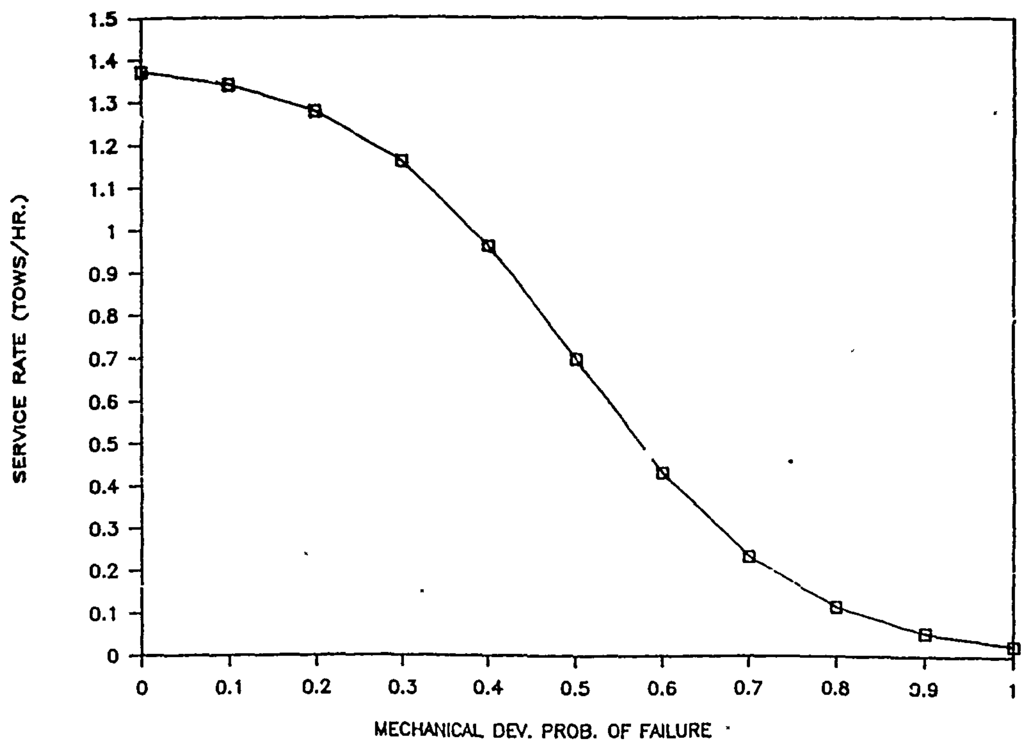


Figure 36. Relationship between service rate and mechanical probability of failure

expressed by the weighted sum of the variance of its components. Therefore, the following functional relationship can be identified between σ, σ_{GCI}, σ_{WCI}, and Mfail:

$$\sigma[t] = a_4 * \sigma_{GCI}[t]^2 + b_4 * \sigma_{WCI}[t]^2 + c_4 * Mfail[t]^2 \tag{52}$$

where $\sigma[t]$ = standard deviation of service time in year t

a_4, b_4, c_4 = coefficients (weighting factors)

$\sigma_{GCI}[t]$ = standard deviation of gate condition index in year t

$\sigma_{WCI}[t]$ = standard deviation of wall condition index in year t

Mfail[t] = mechanical equipment probability of failure in year t

244. Mfail is assumed to be a Poisson process. Therefore, its variance is simply the square of the mean, resulting in the $(Mfail[t])^2$ term in Equation 51 (Drake 1967). The variances of σ_{GCI} and σ_{WCI} are simply their squares; therefore, $\sigma_{CGI}{}^2$ and $\sigma_{WCI}{}^2$ are included in the expression. The coefficients

a_4, b_4, and c_4 are the weighting factors. Their magnitudes reflect the effects of a particular independent variable on the total deviation σ.

Network queuing model

245. All the queuing models described above assume one lock as an independent entity. They assume that no matter how a lock operates, it does not affect the performance of the lock upstream or downstream, which may not be true in some instances. For example, if two locks are very close, the departure process of one lock is the arrival process of the second lock. If the service process of one of the locks is changed due to maintenance, the arrival process of the next lock and the delay at the next lock is also changed. Therefore, the change in the service parameters of one lock has an effect on the performance of nearby locks.

246. Howe et al. (1969) found in their simulation that the impacts of an improvement may be felt throughout the system or at points far removed from the actual improvement. At high traffic densities, when delay time and waiting lines at locks are long, the benefits accruing to the total system from alleviating the congestion at a particular lock (through structural improvement of the lock) are substantially less than the benefits measured only at the point of improvement. Wilson (1978) has also pointed out that where successive locks on a waterway are close enough together, the arrivals at one lock tend to be regulated by service patterns at adjacent locks. This can be called a network effect. Thus, a queuing model that can capture the network effect seems to be more appropriate than the ones described earlier.

247. Because of the complexity involved, there are few network queuing models; and, all of them are approximation models rather than exact models. The major difficulty in the network queuing model is in determining the probability distribution function of the departure process. Whitt (1984) and Albin and Kai (1986) have derived some approximation methods for the departure process of queues in a network. Whitt (1984) described the stationary-interval method. In this method, the stationary-departure distribution is approximated by simple mixture; with probability ρ (utilization ratio) it is the service time and with probability $1-\rho$ it is the service time plus an independent interarrival time. Marshall (1986) has derived a formula for computing the variance of the departure process. For M/G/1 queue,

$$Var(d) = \sigma^2 + (1-\rho^2)/\lambda^2 \tag{53}$$

where $Var(d)$ = the variance of the departure process

σ^2 = the variance of the service time distribution

ρ = the traffic intensity or utilization ratio = λ/μ

λ = traffic arrival rate

248. In fact, the variance computed by using the stationary-interval method for M/G/1 queue complies exactly with Marshall's formula.

249. To capture the network effect of lock performances, locks are modeled as in Figure 37. The arrival distribution at Lock No. 1 is Poisson, and the arrival distribution at Lock No. 2 is computed by using a method similar to the stationary-departure distribution method described above. Lock No. 1 is modeled as M/G/1 queue, and Lock No. 2 is modeled as G/G/1 queue.

250. Howe et al. (1969) have done some simulation with a number of locks in series. From their simulation result, they found that relevant locks seem to be the adjacent locks. In other words, the effect of congestion at a lock seems to be transferred only to one lock upriver and one lock downriver. Therefore, the model in Figure 37 consists of only two locks at a time. When considering downstream traffic delay, use the model as shown in Figure 37. When considering upstream traffic delay, reverse the lock numbers and the direction of traffic. A series of locks can be decoupled into pairs of locks.

251. There is a closed-form formula to compute the average delay for M/G/1 queue. However, there is no closed-form formula to compute the average delay for G/G/1 queue. An approximation formula is acceptable for most applications. The formulas for M/G/1 and G/G/1 queue are as follow:

M/G/1 queue:

252. Pollaczek-Khintchine formula:

$$W = \frac{1}{\mu} + \frac{\rho^2 + \lambda^2 \sigma^2}{2\lambda(1-\rho)} \tag{54}$$

where W = locking time, in hours (equivalent to T_L in Equation 16)

$\frac{1}{\mu}$ = miscellaneous delay time, in hours (equivalent to T_o in Equation 16).

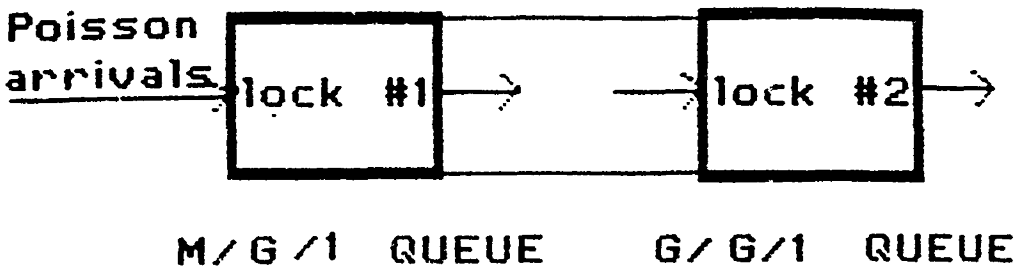


Figure 37. The network queue model

G/G/1 queue:

253. Kraemer and Langenback-Belz formula: (approximation)

$$W = \frac{1}{\mu} + \frac{\lambda \left(C_a^2 + C_s^2\right)}{2\mu^2 (1-\rho)} B \tag{55}$$

where C_a = arrival time distribution

$C_a^2 = \sigma_a^2/(1/\lambda)^2 = \lambda^2 \sigma_a^2$ (the squared coefficient of variations of arrival time distribution)

C_s = service time distribution

$C_s^2 = \sigma_s^2/(1/\lambda)^2 = \lambda^2 \sigma_s^2$ (the squared coefficient of variations of service time distribution)

$B = \exp\left[-2(1-\rho)(1-C_a^2)/3\rho(C_a^2 + C_s^2)\right]$ if $C_a^2 < 1$

$B = \exp\left[-(1-\rho)(C_a^2-1)/(C_a^2 + 4C_s^2)\right]$ if $C_a^2 \geq 1$

254. The M/G/1 queue formula is used to compute the average delay at Lock No. 1; all the parameters needed to compute that are available. The G/G/1 queue formula is used to compute the average delay at Lock No. 2. All the parameters except σ_a^2 are given or can be available. Now, σ_a^2 needs to be computed.

255. Similar to the stationary-departure distribution method, the departure distribution can be computed as follows:

$$f_t^T(s) = \rho_1 S_1(s) + (1-\rho_1) A_1(S) * S_1(s) \tag{56}$$

where $f_t^T(s)$ = Laplace Transform of the departure distribution

$S_1(s)$ = Laplace Transform of the service time distribution at Lock No. 1

$A_1(s)$ = Laplace Transform of the arrival time distribution at Lock No. 1

$*$ = convolution of two distributions

ρ_1 = utilization ratio of Lock No. 1 = λ/μ_1

256. As an example, if the service time is γ^{th} order Erlangian distribution, the mean and variance of the departure process can be computed as follows:

$$f_t^T(s) = \rho_1\left(\frac{\gamma\mu_1^{\gamma}}{s+\gamma\mu_1}\right) + (1-\rho_1)\left(\frac{\lambda}{\lambda+s}\right)\left(\frac{\gamma\mu_1^{\gamma}}{s+\gamma\mu_1}\right) \tag{57}$$

$$E[a] = -\left.\frac{df_t^T(s)}{ds}\right|_{s=0} = \frac{1}{\lambda} \tag{58}$$

$$E[a^2] = -\left.\frac{df_t^T(s)}{ds^2}\right|_{s=0} = \frac{2(1-\rho_1)}{\lambda}\quad \frac{1}{\lambda} + \frac{1}{\mu_1} + \frac{\gamma+1}{\gamma\mu_1^2} \tag{59}$$

$$\sigma_a^2 = E[a^2] - E^2[a]$$

$$= \frac{1}{\lambda^2} - \frac{1}{\mu_1^2} + \frac{1}{\gamma\mu_1^2}$$

$$= \sigma_s^2 + \frac{1}{\lambda^2}(1-\rho_1^2) \tag{60}$$

257. Since all the parameters needed to compute the average delay at Lock Nos. 1 and 2 are available, some sensitivity analysis can be done to determine the effect that a change in one of the parameters will have on the

system delay. This can be directly correlated to maintenance because the effect of a maintenance activity can be translated into change of at least one of the service parameters used in the queuing model. Thus, for each maintenance activity, one can compute the system delay.

Sensitivity analysis

258. The objective of sensitivity analysis is to capture the network effect on the model given in Figure 37. This can be done by changing the values of variables associated with Lock No. 1 and determining the effect in the system delay. A reference line is needed to compare the system delay. Therefore, let the reference line be the system delay of two M/G/1 queues. That is, compute the total delay as a sum of Lock No. 1's delay from M/G/1 model and Lock No. 2's delay also from M/G/1 model. This kind of model assumes that the locks are independent. Therefore, σ_2 in the independent queue model is simply $1/\lambda$ (i.e., the standard deviation of a Poisson distribution). Thus, in the independent queue model, σ_2 is no longer unknown.

259. Three variables are associated with Lock No. 1: λ, μ_1, and σ_1. Although λ is not directly associated with Lock No. 1, its magnitude affects the departure process of Lock No. 1. The following three scenarios were used to do the sensitivity analysis:

a. Scenario 1: The average arrival rate, λ, varies from 0.5 to 1.95 tows/hr. The average service rate at Lock Nos. 1 and 2 remains at 2.0 tows/hr, and the standard deviation of service time at Lock Nos. 1 and 2 remains at 0.5 hr/tow.

b. Scenario 2: Average service rate at Lock No. 1, μ_1, varies from 1.65 to 3.0 tows/hr. The average arrival rate remains at 1.6 tows/hr and the standard deviation of service time at Lock Nos. 1 and 2 remains at 0.5 hr/tow.

c. Scenario 3: Standard deviation of service time at Lock No. 1, σ_1, varies from 0.05 to 2.5 hrs/tow. The average arrival rate remains at 1.6 tows/hr and the average service rate at Lock Nos. 1 and 2 remains at 2.0 tows/hr.

260. In scenario 1, the arrival rate at Lock No. 1 is varied. Figure 38 shows the effect of arrival rate on system delay. The system delay for the dependent queue (the model of Figure 37) and that for independent queues are

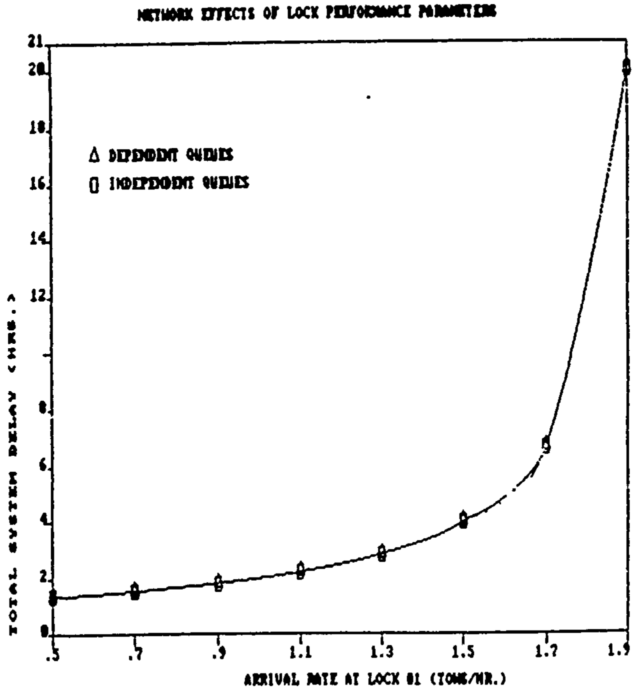


Figure 38. Total system delay versus arrival rate (scenario 1)

the same. As arrival rate increases, the system delay also increases. As the arrival rate approaches Lock No. 1's service rate, the system delay approaches infinity.

261. In scenario 2, the service rate of Lock No. 1 is varied. Figure 39 shows that as the service rate at Lock No. 1 increases, the delay at Lock No. 1 decreases, but the delay at Lock No. 2 increases. The reason for Lock No. 2's increase in delay could be because the bottleneck or the congestion is transferred from Lock No. 1. For example, if two barges arrived at Lock No. 1 with a very small arrival time difference, they will be serviced in less time and both will arrive at Lock No. 2 with small time difference. The second tow will have to wait until the first one is through. Thus, the average delay at Lock No. 2 increases. Figure 40 shows the total system delay for the dependent and independent queue. The system delay for both models is not that different, and the result may mean a number of things. First, although the difference between the two models is not much for this particular set of values, the difference could be much larger for some other combination of

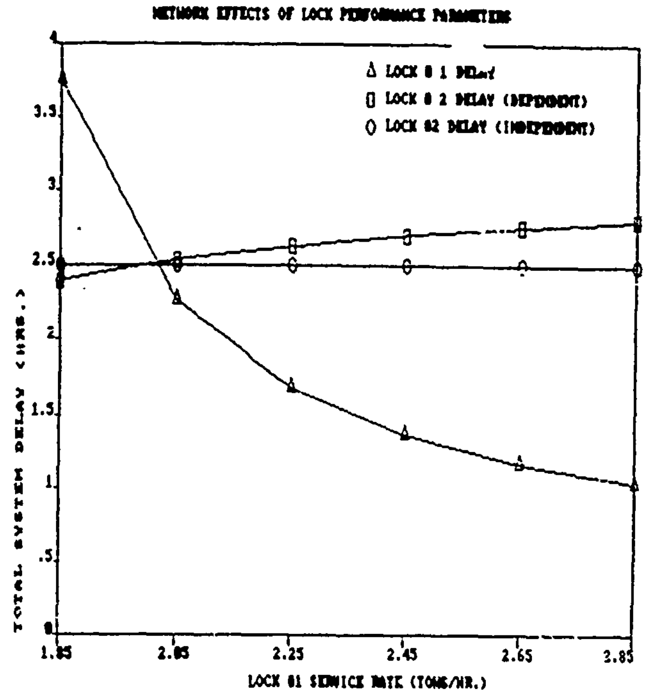


Figure 39. Delay at Lock No. 1 and Lock No. 2 versus service rate at Lock No. 1 (scenario 2)

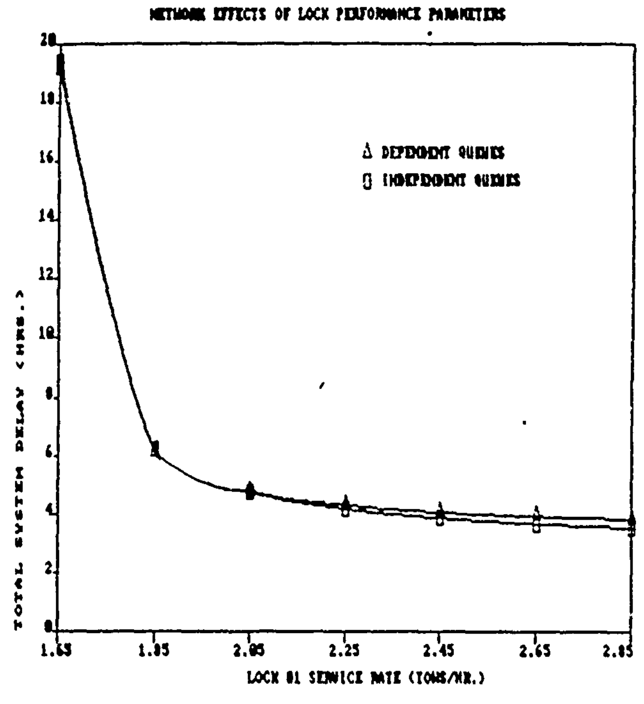


Figure 40. Total system delay versus service rate at Lock No. 1 (scenario 2)

values. Second, if the congestion is just transferred to the other lock, the reduction in system delay is very small; therefore, it might not be justifiable to improve the service rate of Lock No. 1 only.

262. In scenario 3, the standard deviation of service time at Lock No. 1 is varied. Figure 41 shows that as the standard deviation of service time (σ_1) increases, the system delay also increases. When the standard deviation of service time (σ_1) is equal to 0.5 hr/tow, the squared coefficient of variation of service time at Lock No. 1 is equal to 1. The distribution is the same as the Poisson distribution. Therefore, the system delay is the same using either model. When σ_1 is less than 0.5 hr/tow, the system delay of the dependent queue is less than that of the independent queue. When σ_1 is greater than 0.5 hr/tow, the reverse is true. When σ_1 is less than 0.5 hr/tow, the service time is less random than the Poisson distribution; therefore, the average delay at Lock No. 1 is less and the randomness of the departure process of Lock No. 1 is also small. When σ_1 is greater than 0.5 hr/tow, the service time is more random than the Poisson distribution; therefore, the average delay at Lock No. 1 is high, and the randomness of the departure process of Lock No. 1 is also high. When σ_1 is less than 0.5 hr/tow, Lock No. 1 is working as a filtering object, and when σ_1 is greater than 0.5 hr/tow, Lock No. 1 is working as a clustering object. Based on scenario 3, reducing the standard deviation of service time at locks could be the most effective approach to reduce the system delay. Figure 41 is for highly used (congested) locks. Figure 42 shows the difference in system delay for the two models for less congested locks. The difference between the dependent and independent queuing models is not that significant.

Incorporating the network model in a system

263. The above model was used to compute system delay for a system that consists of only two locks. Usually, more than two locks are along a river, and traffic operates in both directions. To compute the delay for upstream traffic and downstream traffic, another variable, the proportion of upstream traffic to the total traffic going through the lock is needed.

264. To compute the average downstream traffic delay at a lock, one should check how far is the next upstream lock from the particular lock being considered. If it is more than some limiting distance upstream (LU), it is less likely that the performance of the upstream lock will affect the lock

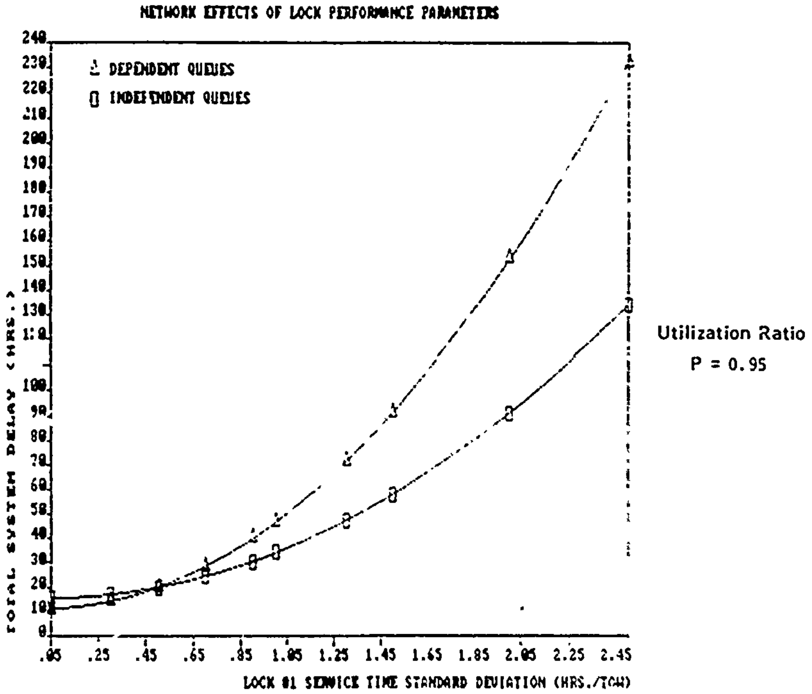


Figure 41. Total system delay versus standard deviation of service time at Lock No. 1 (scenario 2) with high utilization ratio

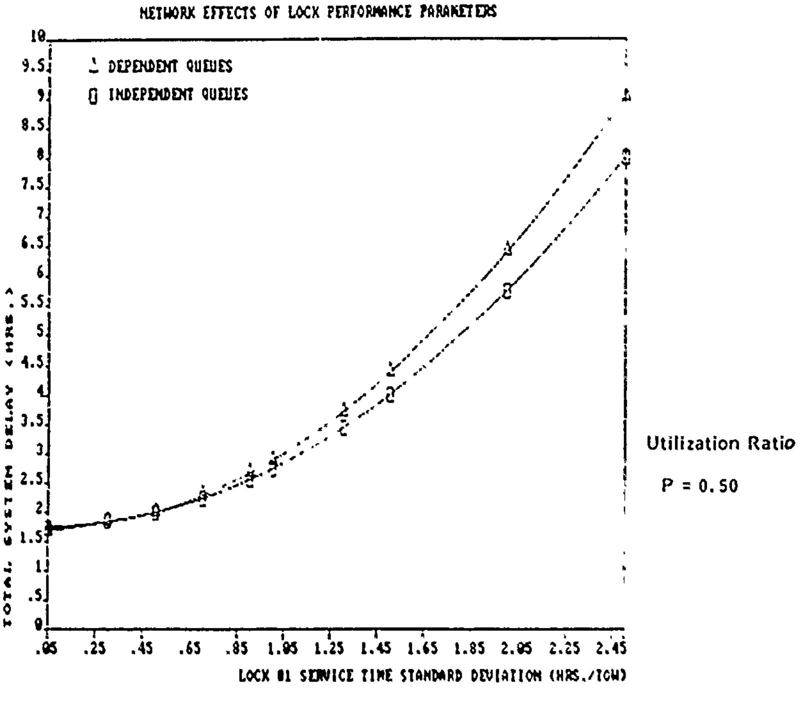


Figure 42. Total system delay versus standard deviation of service time at Lock No. 1 (scenario 3) with low utilization ratio

being considered. A number of random processes could happen between the upstream lock and the lock being considered to affect the traffic arrival process. At that point, it is more reasonable to assume as a Poisson process than anything else. But, if the distance between them is less than LU miles, it is likely that the departure process of the upstream lock is very similar to the arrival process of the lock being considered. Therefore, if the distance between the next upstream lock and the lock being considered is less than LU miles, G/G/1 queuing model is used to compute the average downstream traffic delay. The arrival process of the G/G/1 queue is approximately the departure process of the next upstream lock. If the distance between the next upstream lock and the lock being considered is greater than LU miles, M/G/1 queuing model is used to compute the average downstream traffic delay, and the arrival process at Lock No. 2 is assumed to be a Poisson process. Similarly, to compute the average upstream traffic delay at the lock, if the distance between the lock being considered and the next downstream lock is less than LD miles, use G/G/1 queuing, otherwise use M/G/1 queuing. Let us denote the average upstream and downstream delay by Wu and Wd, respectively. Then, the annual traffic delay, W, is computed as follows:

$$W = T\,[pu * Wu + (1 - pu) * Wd] \tag{61}$$

where W = annual traffic delay in tow-hr

T = annual traffic at the lock in tows/yr

pu = the ratio of upstream to total traffic at the lock

Wu = average upstream traffic delay at the lock

Wd = average downstream traffic delay at the lock

265. Once the annual traffic delay is determined, compute the delay cost for that year using the following formula:

$$Dc = W * dc \tag{62}$$

where Dc = user cost for a given year in dollars

W = traffic delay for that given year in tow-hr

dc = average tow delay cost per hour ($/hr)

266. One can similarly compute the annual delay costs for the entire planning horizon and, by summing them (discounted sum), obtain the total delay cost for the planning period.

Downtime cost

267. Downtime cost is the cost incurred by the user due to close down of a lock because of the maintenance or inspection activity. The downtime cost is a function of the length of downtime and average cost of downtime. As discussed in Part II, the traffic can be forecast and the Corps maintains data on the average costs per tow per hour of closing the lock. Empirical evidence was used to establish average downtime per year.

268. The reconnaissance reports for Montgomery included the number of days each chamber was closed during the year. These data are summarized in Table 16. Closings due to motor vessel damage were assumed to be scheduled. The amount of time the lock is closed is important for two reasons. First, closing the lock impacts the service rate and users. The magnitude of impacts in terms of delay, diversion, and inventory costs are not quantified in this preliminary analysis. Second, the amount of time the lock is closed may be a surrogate for condition. Figure 43 is a plot of cumulative maintenance expenditures versus cumulative scheduled and unscheduled downtime. In recent years, the number of days the lock is closed has increased far more rapidly than in the past. Although this analysis is preliminary, it indicates another approach to estimating deterioration, setting maintenance standards in terms of maximum number of days closed per year, and estimating requirements.

269. The downtime cost is computed using the following formula:

$$Mc = S * T/365 * v \tag{63}$$

where Mc = downtime cost in dollars for a year

S = scheduled and unscheduled downtime for the lock in days/yr

T = total annual traffic at the lock (tons/yr)

v = average cost associated with 1 hr close down per potentially arriving tow ($/tow)

Table 16

Montgomery Lock Closure Data by Cause

Cause	Av No. Days Closed/Yr	Av No. Days /Closing
Main		
Repair/rehab	6.2	14.0
MV damage	1.5	4.3
Auxiliary		
Repair/rehab	2.7	10.4
MV damage	0.1	4.0

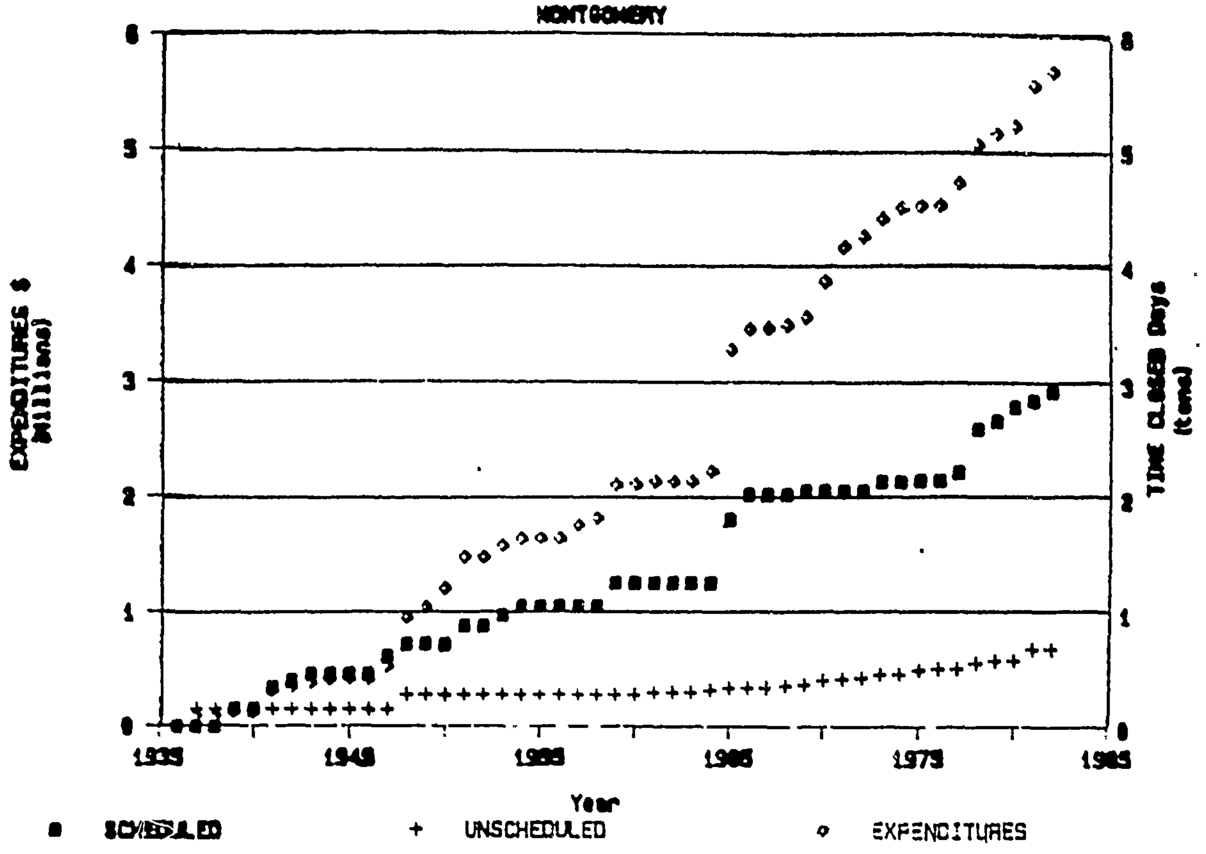


Figure 43. Lock closure data by type for Montgomery Lock

The scheduled and unscheduled downtimes are computed using the following equations:

$$Ss = \max \frac{(Gs,\ Ws,\ Ms)^2}{2} \tag{64}$$

where Ss = scheduled downtime in a year (days/yr)

Gs = scheduled gate maintenance downtime (days/yr)

Ws = scheduled wall maintenance downtime (days/yr)

Ms = scheduled mechanical equipment maintenance downtime (days/yr)

$$Sus = \Sigma \frac{(k * inc\_prob)^2}{2} \tag{65}$$

where Sus = unscheduled downtime in a year (days/yr) for lock gates, lock walls, and mechanical equipment

k = average number of days needed to carry out an unscheduled maintenance activity

inc_prob = incremental probability of failure

$$Gus \text{ or } Wus \text{ or } Mus = inc\_prob. \tag{66}$$

where Gus = unscheduled gate maintenance downtime (days/yr)

Wus = unscheduled wall maintenance downtime (days/yr)

Mus = unscheduled mechanical equipment maintenance downtime (days/yr)

270. For gates and walls, inc_prob is the incremental probability that the gate or wall condition index will fall below the standard condition index. The distribution that defines these probabilities has already been discussed in terms of the expected value of the condition index (Equation 5) and the standard deviation of condition index (Equation 2). For mechanical equipment, inc_prob is equal to Mfail(t) - Mfail (t-1). Finally,

$$S = Ss + Sus \tag{67}$$

Total user costs

271. Once the total delay cost and downtime cost is computed, compute the total user cost for a given year using the following equation:

$$Uc = Dc + Mc \tag{68}$$

where Uc = total user cost in dollars in a given year

Dc = total delay cost in dollars for that year

Mc = total downtime cost in dollars for that year

272. Compute the annual total user cost for the entire planning horizon and sum them (discounted sum) to get the discounted user cost for the entire planning period.

PART V: DEVELOPMENT OF A PROTOTYPE SYSTEM

273. Part II presented the general concepts of life-cycle costing as applied to the management of facility repair, evaluation, maintenance, and rehabilitation. These concepts were then developed more fully in terms of technical and cost relationships applied to waterways locks, as described in Parts III and IV. In this part, these ideas and procedures are brought together by illustrating the operation, use, and interpretation of results of a prototype REMR Management System.

274. The prototype system embodies the key concepts and features of the final package, but in a simplified and preliminary way. For example, technical and cost relationships are structured to fully capture those aspects of demand-responsive maintenance discussed in Parts II through IV, particularly the effects of REMR activities on facility performance and life-cycle costs. However, these relationships have not yet been calibrated to specific projects and environments. Also, the prototype relies upon a limited data base for simplicity and ease of illustration; more extensive and general data base management capabilities need to be developed for the final version of the system.

275. Not all potential analytic capabilities have been included in the prototype. For example, optimization procedures (e.g., to identify the "best" REMR policies subject to budget constraints) may be a desirable addition, but such procedures require further research. Also, the prototype system is limited to locks. The final Management System will likely address several types of facilities.

276. Apart from these technical concerns, however, all of the other features of the prototype system (e.g., command menus, editing capabilities, and control options) mimic the capabilities of the full Management System. This part will illustrate these capabilities and demonstrate how they might be applied in realistic management situations. The data and results presented later in this chapter will be more correct in trend than in value, but should nevertheless provide a sufficient basis for identifying needed additions and modifications to be addressed in future research.

277. Figure 44 shows a flowchart of the prototype REMR Management System. Functions are organized at three basic levels:

a. Description of the problem to be analyzed and the REMR policies to be tested. These data are provided through commands and data input by the user (top of Figure 44).

b. The analytic core, comprising all procedures needed to predict the structural and operational performance and related life-cycle costs of the lock facility (central portion of Figure 44).

c. The tallying and reporting of results (set of cost reports at the bottom of Figure 44).

278. The operation and use of the Management System would proceed in the order implied above. The cycle would be repeated for each REMR policy to be tested. To present and explain the prototype system, however, it will be clearer to begin with the specific equations used in the prototype and then relate these equations to both the problem descriptions input by the user and the results obtained. In this way the meanings and uses of the several input parameters can be defined unambiguously and explained within their proper context. Similarly, the content and interpretation of the results can be tied analytically to the specific prediction models used.

Estimation of Deterioration Model Parameters

Background

279. Knowledge of facility deterioration is central to the demand-responsive approach to REMR activities, as described in Part II. Projections of REMR requirements, costs, and impacts to both users and the owning agency are based directly upon predictions of facility condition. Therefore, good models of condition or deterioration are important to a REMR Management System. Furthermore, these models ideally should relate the current condition and rate of deterioration to current and past REMR performed. Suggested forms of these models were derived and presented in Part III, Equations 1 through 6.

280. Unfortunately, the estimation and calibration of these kinds of models is complicated by the absence of an objective, well-defined measure of condition, the lack of sufficient historical data, and the difficulty of relating the condition to REMR actions performed. Although the Corps does

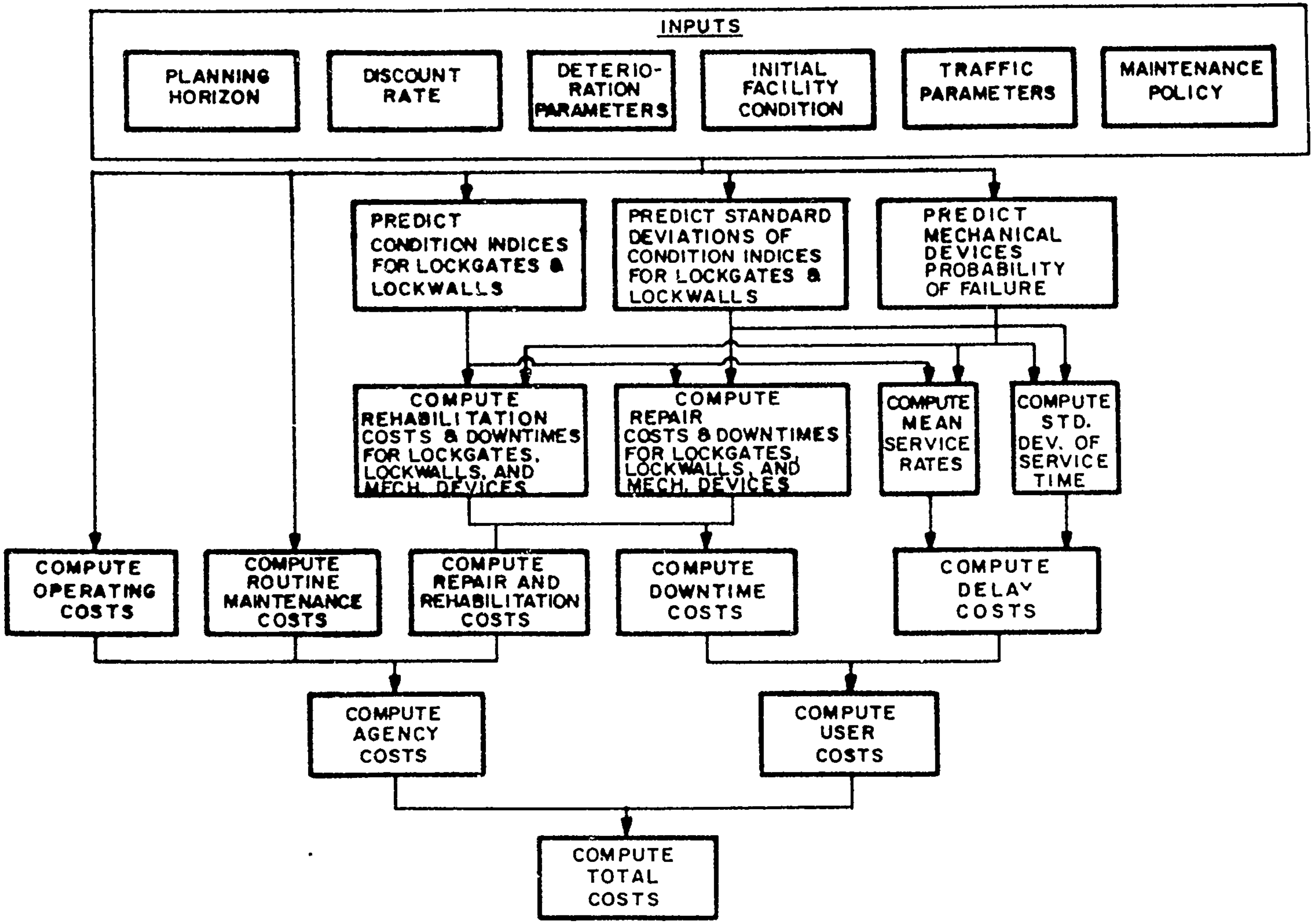


Figure 44. Flowchart of the Prototype REMR Management System

keep extensive records on work performed at each lock and dam, these data do not contain any quantitative information on trends in condition indices (or the probability of failure of mechanical equipment) as a function of time or of REMR policy. Although it is possible that these data could subsequently be analyzed to obtain the desired relationships, a different approach had to be found for this project.

General approach

281. If facilities deteriorated steadily, essentially having some percentage of their structural and operational capacity consumed each year, deterioration models would be relatively easy to estimate by monitoring the rate of annual consumption or noting the age at which a facility had reached the end of its service life. However, facility condition in fact does not decline inexorably toward failure. The progression of damage, aging, and wear is interrupted by repairs and rehabilitation. Although these actions may not restore the condition of a facility completely to its as-built state, they do confer some substantial improvement, lengthen facility life, and preserve the safety, efficiency, and cost-effectiveness of facility operation. From an analytic perspective, this cycle of decline and renewal is visualized as a sawtooth-shaped curve as shown in Figures 12 and 15.

282. The approach used to estimate facility deterioration functions therefore must account for the effects of REMR activities. Given the lack of quantitative data on these effects, they must be estimated from available information. The research used the REMR cost data from 1931 to 1981 for the Emsworth, Dashields, and Montgomery locks and dams. These costs will serve as indicators for the type and the level of REMR activities that historically have been performed at these facilities. These data will be used to estimate the frequencies and amounts of improvement in facility condition due to repairs and rehabilitation. Although routine maintenance is also a REMR activity, it affects the standard deviation of condition index, not its expected value or mean, and therefore is not considered in the estimating process described here.

283. An estimate of the total service life of each facility component was also used. The total service life is a function of both the rate of deterioration of the component and the REMR activities performed. The REMR activities performed under a given policy have already been estimated as

described earlier. Therefore, if that estimate is taken together with the judgment of total service life, one can infer the rate of deterioration that has taken place in the interval between successive REMR actions (i.e., one can estimate the time-related deterioration represented by Equations 2, 5, and 6). The following paragrahs describe how this was done for the prototype model.

Model estimation and calibration: some examples

284. To illustrate the procedure of model estimation and calibration, consider first the lock gates. Figure 45 shows a set of deterioration curves representing various REMR efforts. Curve 1 is an estimate of the hypothesized trend in the gate condition index if no repairs or rehabilitation were performed. It is based on an expected life of 50 years under these conditions. The curve is concave, with the rate of deterioration increasing as the facility grows older.* One could view Curve 1, therefore, as a basic or "pure" deterioration trend.

285. As noted earlier, activities occur at different intervals and range from minor repairs to major rehabilitations. Although frequency data can be obtained from past records, the level of effort must be estimated from the cost of the project. The model needs to quantify the amount of improvement in condition, Δ, resulting from each REMR activity.** Since data are not available in this form, project costs are used as a surrogate to estimate Δ.

286. An analysis of project histories revealed different categories of projects, occurring at different intervals, and entailing different magnitudes of project cost. In fact, the project costs appeared to be clustered within well-defined groups. Therefore, for the model, four different ranges of project costs were used to correspond to four catagories of REMR activities. The activities with costs less than $100,000 were assumed to be minor repairs, activities with costs between $100,000 and $200,000 were major repairs, activities with costs between $200,000 and $600,000 were minor rehabilitation,

* The estimates are based on assumptions from the information currently available. This procedure can be repeated for other assumptions or to account for additional data from other facilities. Also, note that facility life is arbitrarily defined as that point where the condition index is zero. Again, this assumption can be modified if desired, with no loss of generality in the approcah that is described.

** Refer to Part III for the use of Δ in facility models.

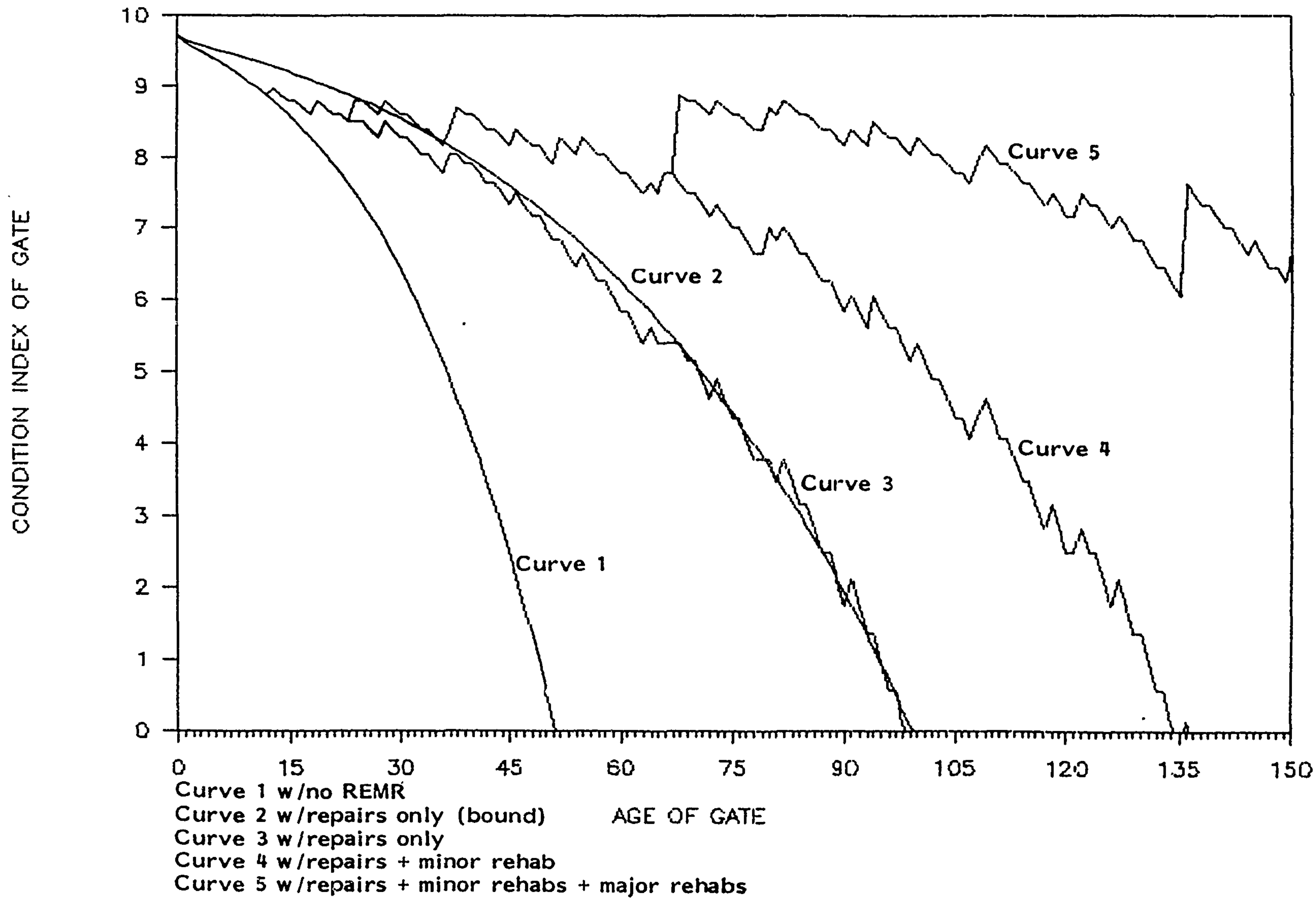


Figure 45. Effects of REMR policies on the Lock Gate Condition Index

and activities with costs over $600,000 were major rehabilitation. The average frequencies and costs for the four different catagories of REMR activities for lock gates are listed in Table 17.

287. In Figure 45, Curve 2 represents the hypothesized, smoothed trend in the gate condition index if only minor and major repairs were performed. This is based on an expected life of 100 years under these conditions. Although repairs to lock gates would not prolong the expected life indefinitely, this expected life is a reasonable assumption that appears to be consistent with the historical data in Part I.

288. Curve 2 was then used as a guide to which the sawtooth-shaped curve (Curve 3), explicitly including the effects of minor and major repairs, could be fit. Curve 3 was obtained by superimposing the different levels of effort (i.e., Δs) of minor and major repairs every 3 and 8 years, respectively. Appropriate values of Δ were estimated based upon two criteria: (a) the relative project costs (from Table 17), as an indication of relative level of effort and degree of improvement in gate condition, and (b) the need for Curve 3 to track Curve 2 as closely as possible.

289. This process was then repeated for rehabilitation. Curve 4 was obtained by superimposing minor rehabilitations (at the frequency and level of effort implied by Table 17) on Curve 3. This was based on the assumption that the expected life of the facility with repairs and minor rehabilitation would be 135 years.

Table 17

Average Costs and Frequencies of REMR Activities

REMR Activity	Cost Range (1977 $)	Average Frequency (in years)	Average Costs (1977 $)
Minor repairs	<100,000	3	37,290
Major repairs	100-200,000	8	156,652
Minor rehabilitation	200-600,000	13	412,377
Major rehabilitation	600,000	50	1,232,204

290. Similarly, Curve 5 was obtained when major rehabilitations in the frequency of every 50 years were added to Curve 4. Thus, Curve 5 represents the trend in the condition index of lock gates when minor and major repairs and minor and major rehabilitation in their corresponding frequencies are added to Curve 1. The value of the corresponding Δ for major rehabilitation was estimated by assuming that this activity, when combined with all others, should yield a condition of lock gates of about 6.5 in 150 years. The general trend of Curve 5 is decreasing, implying even with periodic rehabilitation, the lock gates will need to be replaced.

291. The estimated values of Δ for different levels of REMR activities from Curves 3, 4, and 5 are listed in Table 18. As the level of REMR effort increases, the value of Δ also increases. These values not only affect the calibration of coefficients in the deterioration model equations, but also are used directly in the prediction models for repair and rehabilitation costs.

292. Using a similar approach, corresponding deterioration curves for lock walls and mechanical equipment were produced. The trends of the condition index of lock walls and mechanical equipment over time are displayed in Figures 46 and 47, respectively. These curves illustrate the basic tenets of the demand-responsive approach; the facility condition over time is affected by REMR policy, and this trend in condition is used to predict the costs and impacts of different policies. Although the relationships in Figures 45 through 47 need to be validated in the field, they are reasonable in trend, are in general agreement with observed lives of facilities as summarized in Part I, and serve to illustrate how the demand-responsive approach described in Part II can be implemented in a practical way.

Table 18

Amount of Improvement in Condition

REMR Activity	Estimated Δ
Minor repairs	0.042
Major repairs	0.17
Minor rehabilitation	0.30
Major rehabilitation	1.10

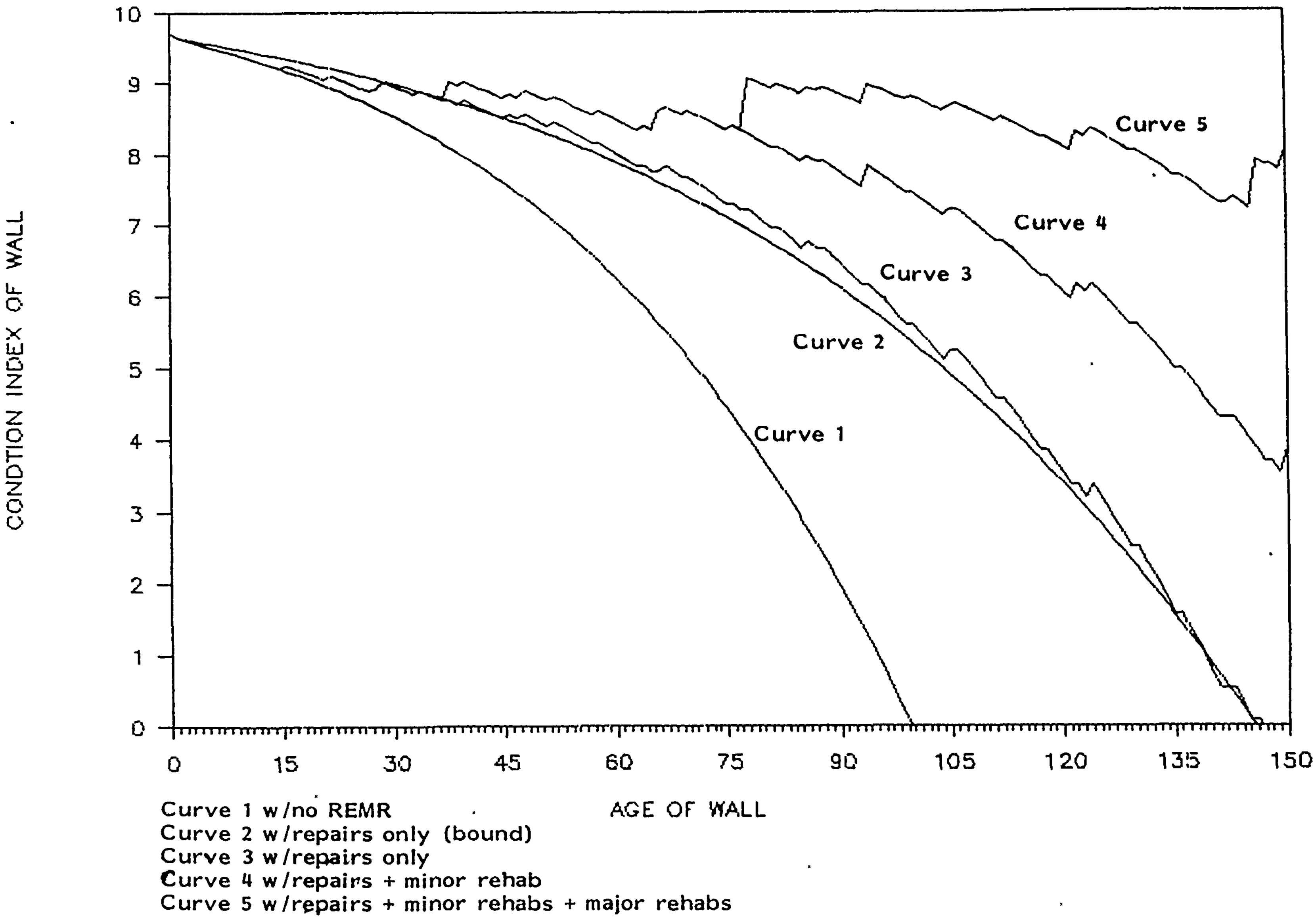
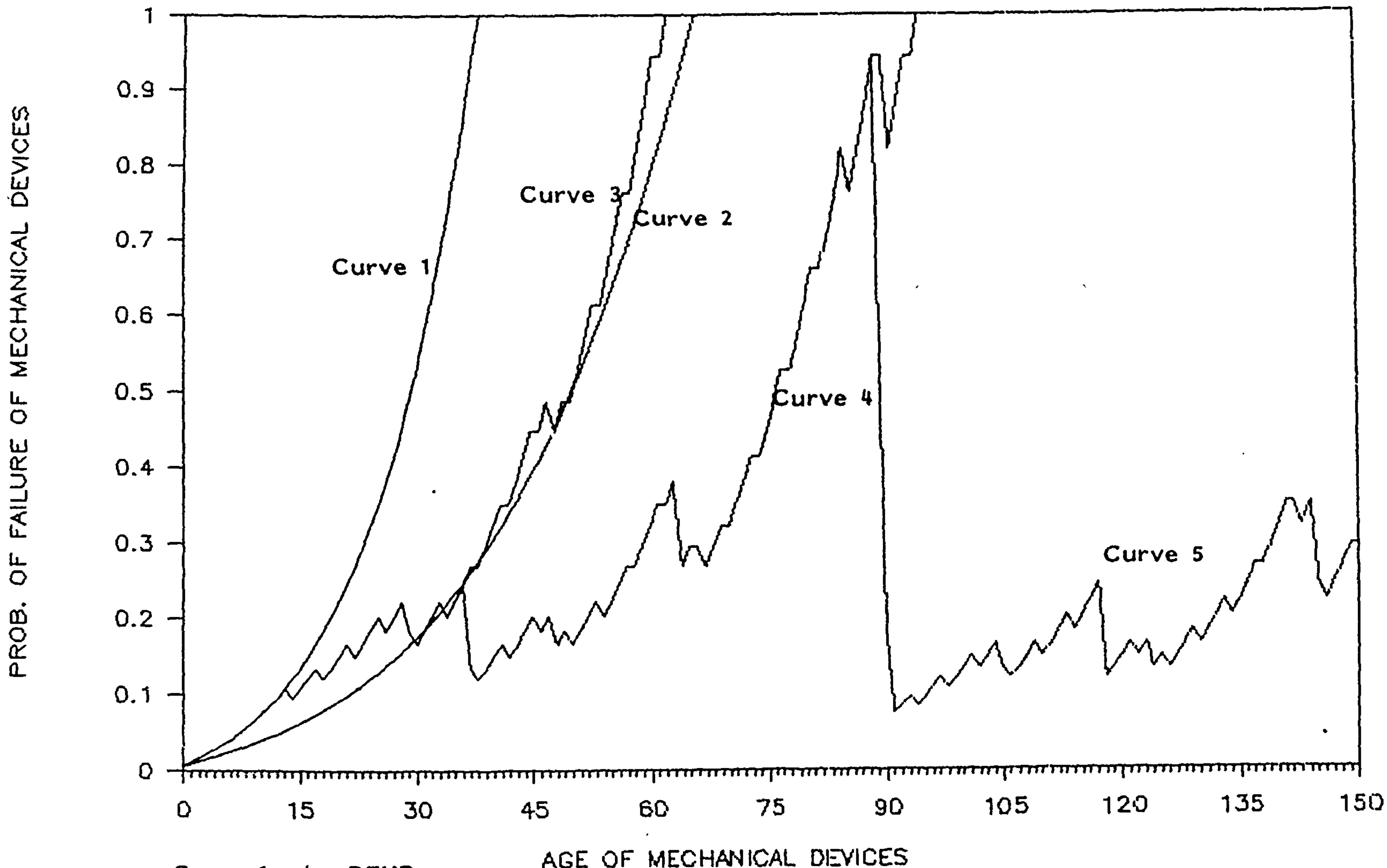


Figure 46. Effects of REMR policies on the Lock Wall Condition Index



Curve 1 w/no REMR
Curve 2 w/repairs only (bound)
Curve 3 w/repairs only
Curve 4 w/repairs + minor rehab
Curve 5 w/repairs + minor rehabs + major rehabs

Figure 47. Effects of REMR policies on the probability of failure of mechanical equipment

Prototype Models

293. The following paragraphs describe the models and relationships used in the prototype REMR Management System. In most cases, these models represent refinements or specific examples of the more general approaches suggested in Parts III and IV. Their primary purpose is to illustrate how the demand-responsive and life-cycle cost concepts introduced in Part II may be reduced to actual practice.

Traffic growth

294. Traffic volume determines both the use of the lock (affecting REMR requirements and costs discussed in Part III) and the impacts of lock performance as affected by REMR policy (the costs and benefits discussed in Part IV). Given the very long service lives of lock facilities (see Part I), it is unrealistic to expect that traffic growth can extend uniformly throughout the entire analysis period. Therefore, it is conventional to specify some growth rate for a limited number of years only. The traffic will then become asymptotic to some maximum anticipated volume. The relationship used to represent traffic growth is as follows:

$$T_t = A - B * \exp(-c * t) \tag{69}$$

where T_t = the annual traffic in tows in year t

$A = (1\text{+growth rate}/100)^{\text{growth years}} * \text{growth start}$

B = A-growth start

C = 0.20 (coefficient)

This relationship is illustrated graphically in Figure 48.

Facility condition

295. Facility condition in a particular year is defined by the measures listed below.

a. For lock gates and lock walls:

(1) Expected value of condition index.
(2) Standard deviation of condition index.

b. For mechanical devices: probability of failure.

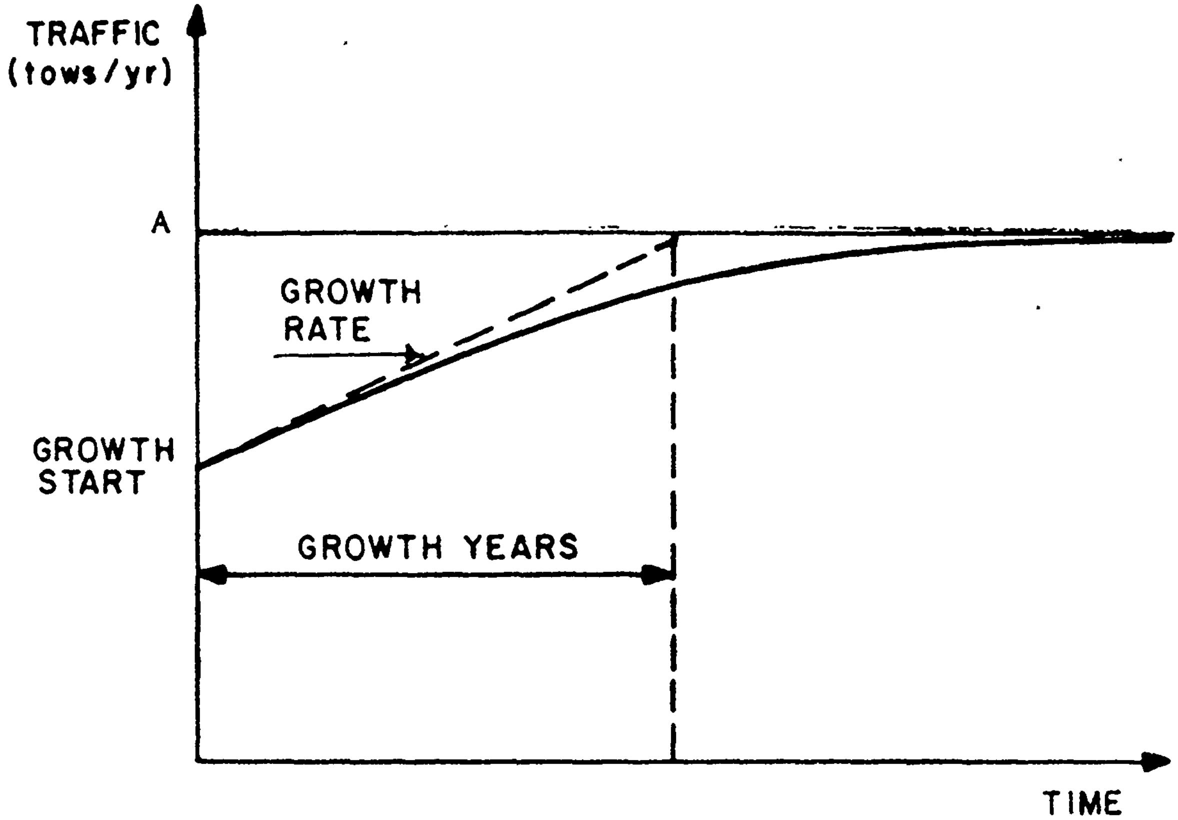


Figure 48. Traffic prediction curve

296. The time-dependent trends in these indices are predicted as follows:

297. Expected value of condition index for lock gates and lock walls.

$$CI[t] = CI_0 - a_1 * \exp\ b_1 * m^{0.5} \tag{70}$$

where $CI[t]$ = condition index in year t

CI_0 = condition index in year 0 or initial condition index

a_1, b_1 = coefficients

m = equivalent age of the lock gates/walls given by the following equation:

$$m = \mathrm{ROUND}\left(\frac{\ln(CI_0 - CI[t]) - \ln a_1}{b_1}^{2}\right) \tag{71}$$

where ROUND is a roundoff function.

298. The default value of CI_0 is 9.8 for both lock gates and lock walls. The values of a_1 and b_1 in Equation 71 are same as that of Curve 1 in Figure 45 and 46 for lock gates and lock walls, respectively. The estimated value of a_1 is 0.10 for lock gates and lock walls and the estimated value of b_1 is 0.64 for lock gates, and 0.46 for lock walls. (The user may change those default values during input and editing, as will be discussed later.)

299. <u>Standard deviation of condition index for lock gates and lock walls.</u>

$$\sigma[t] = \sigma[t-1] * \delta \tag{72}$$

where $\sigma[t]$ = standard deviation of gate/wall condition index in year t

$\sigma[t-1]$ = standard deviation of gate/wall condition index in year t-1

$$\delta = \begin{cases} \sigma_0/\sigma[t-1], & \text{if major rehabilitation is done in year t} \\ 0.75, & \text{if minor rehabilitation is done in year t} \\ a_5 + b_5 * (10 - \text{Routine}[t])^2, & \text{otherwise} \end{cases}$$

σ_0 = standard deviation of gate/wall condition index in year 0

a_5, b_5 = coefficients

Routine[t] = gate/wall routine maintenance policy level (0 to 10 scale) in year t

300. The default values of σ_0 ,a_5 and b_5 are as follows:

$$\sigma_0 = \begin{cases} 0.12 \text{ for lock gates} \\ 0.10 \text{ for lock walls} \end{cases}$$

$$a_5 = 1.01$$

$$b_5 = 0.0008$$

The default value of σ_0 may be changed as described in the previous section. However, in the prototype system the coefficients a_5 and b_5 cannot be cnanged by the user.

301. <u>Probability of failure of mechanical equipment.</u> As described in Part III, the form of the equation is as follows:

$$Mfail[t] = Mfail_0 * \exp(a_2 * m^{0.5}) \tag{73}$$

where $Mfail[t]$ = mechanical devices probability of failure in year t

$Mfail_0$ = mechanical devices probability of failure in year 0

a_2 = coefficient computed from Equation 75 (below)

m = equivalent age of the mechanical devices computed from Equation 76 (below)

$$a_2 = \frac{45}{52 + m\_routine} \tag{74}$$

where m_routine = the routine maintenance policy for mechanical equipment throughout the planning horizon;

$$m = \mathrm{ROUND}\left(\frac{\ln(Mfail[t]) - \ln Mfail_0^{\,2}}{a_2}\right) \tag{75}$$

The estimated value of $Mfail_0$ = 0.005. The parameters of Equation 75 are the same as the parameters of Curve 1 of Figure 47. The user may change the value of $Mfail_0$ during input and editing.

<u>Costs</u>

302. The computation of cost includes the following items:

<u>a</u>. Scheduled Maintenance Costs.

<u>b</u>. Unscheduled Maintenance Costs.

<u>c</u>. Operating Costs.

<u>d</u>. Routine Maintenance Costs.

<u>e</u>. Delay Costs.

<u>f</u>. Downtime Costs.

303. Scheduled Maintenance Costs. The scheduled maintenance costs for lock gates and lock walls are computed by the following relationships:

$$S\_Cost[t] = \begin{cases} 0, \text{ if neither minor nor major rehabilitation is done in year } t \\ a_6 + b_6 * \Delta & \text{if } \Delta \leq \Delta_{max} \\ a_6' + b_6' * \Delta & \text{if } \Delta > \Delta_{max} \end{cases} \quad (77)$$

where $S\_Cost[t]$ = scheduled maintenance cost in year t

a_6, b_6, a_6', b_6' = coefficients

Δ = amount of condition index improvement in year t due to repair or rehabilitation

Δ_{max} = maximum amount of condition index improvement that can be achieved by a minor rehabilitation

304. The values of the parameters in Equation 78 were estimated by using information from the previous section. The average project costs and estimated Δ for each REMR activity and a judgmental guess on the limit of Δs for each REMR activity were used to determine the following cost parameters:

Δ_{max} = 0.6 for lock gates
= 0.5 for lock walls

a_6 = 7,689 for lock gates
= 25,462 for lock walls

b_6 = 1,035,116 for lock gates
= 1,250,190 for lock walls

a_6' = 76.3812 * a6 = 587,295 for lock gates
= 25.567 * a6 = 650.987 for lock walls

b_6' = 0.53403 * b6 = 552,779 for lock gates
= 0.71881 * b6 = 898,652 for lock walls

The ratio of a_6' and a_6 and b_6' and b_6 cannot be changed by user input in the prototype system.

305. The scheduled maintenance costs for mechanical devices are computed using the following equation:

$$M\_S\_Cost[t] = \begin{cases} 0, \text{ if neither minor nor major rehabilitation is done in year } t \\ a_7 + b_7 * \Delta & \text{if } \Delta \leq \Delta_{max} \\ a_7' + b_7' * \Delta & \text{if } \Delta < \Delta_{max} \end{cases} \qquad (77)$$

where M_S_Cost[t] = mechanical device scheduled maintenance cost in year t

a_7, b_7, a_7', b_7' = coefficients

Δ = reduction in the probability of failure in year t due to repair or rehabilitation

Δ_{max} = maximum amount of probability of failure improvement that can be achieved by a minor rehabilitation

306. Values of the parameters in Equation 78 were estimated using information from the previous section. The average project costs and the estimated Δs, and a judgmental guess on the limit of Δ for each REMR activity were used to estimate the parameter values in Equation 78. The estimated parameter values are as follow:

$\Delta_{max} = 0.043$

$a_7 = 7{,}664$

$b_7 = 3{,}406{,}321$

$a_7' = 10.60 * a_7 = 81{,}235$

$b_7' = 3.76 * b_7 = 1{,}527{,}511$

Δ_{max} values cannot be changed by the user in the prototype system.

307. Unscheduled Maintenance Costs. The unscheduled maintenance costs are computed by using the following relationships:

$$US\_Cost[t] = inc\_prob * minor\_maint\_cost \qquad (78)$$

where US_cost[t] = unscheduled gate/wall maintenance cost in year t

inc_prob = incremental probability of gate/wall condition index falling below the failure condition index standard in year t. The expected value of the condition index and

the standard deviation of condition index in year t is already computed above. Therefore, by assuming normal distribution, inc_prob can be easily computed. The failure condition index standard is 1.5 for lock gates and lock walls. For mechanical devices, inc_prob would simply equal Mfail[t] - Mfail[t-1]

minor_maint_cost = expected value of unscheduled minor maintenance cost for lock gates or lock walls or mechanical devices in any year.

Default values are as follows:

minor_maint_cost = $182,355 for lock gates

= $232,260 for lock walls

= $175,440 for mechanical devices

The above costs are based on the average values given in Table 12.

308. Operating Costs. Operating costs may be estimated from the following equation:

$$\text{Op\_Cost}[t] = \text{avg\_lockage\_cost} * \text{lockages} * \text{traffic}\ [t] \quad (79)$$

where Op_Cost[t] = operating cost for lock in year t

avg_lockage_cost = average cost per lockage

lockages = average number of lockages per tow

traffic = traffic in tows/year

Default values are as follows:

avg_lockage_cost = 70.00

lockages = 0.50

309. From the information now available, operating costs are not sensitive to REMR policy. Therefore, they have not been included in the prototype system. If operating costs are desired in future versions of the Management System, they may be included by Equation 80.

310. Routine Maintenance Costs. The routine maintenance costs are computed by using the following relationships:

$$\begin{aligned} \text{R\_Cost}[t] &= a_8 + b_8 * \text{G\_routine}[t]^2 \\ &+ c_8 + d_8 * \text{W\_routine}[t]^2 \\ &+ e_8 + f_8 * \text{M\_routine}^2 \end{aligned} \tag{80}$$

where R_Cost[t] = routine maintenance cost in year t

$a_8, b_8, c_8, d_8, e_8, f_8$ = coefficients

G_routine[t] = routine maintenance policy for gates in year t

W_routine[t] = routine maintenance policy for walls in year t

M_routine = average routine maintenance policy for mechanical equipment for the entire planning horizon

Estimated values of the coefficients are as follows:

$a_8 = 500$

$b_8 = 500$

$c_8 = 500$

$d_8 = 370$

$e_8 = 500$

$f_8 = 370$

These defaults cannot be changed by the user in the prototype system.

311. Delay Cost. As described in Part IV, the average annual service rate and the average annual standard deviation of service time must be computed to estimate the delay cost. The equation used to compute service rate is as follows:

$$\mu[t] = \mu 0 * \frac{\exp[a_3 * (\text{Mfail}[t] - 0.50)]}{\{1 + \exp[a_3 * (\text{Mfail}[t] - 0.50)]\}} \tag{81}$$

$$* \frac{1}{\{1 + \exp[b_3 * (\text{GCI}[t] - 5.0)]\} * \{1 + \exp[c_3 * (\text{WCI}[t] - 5.0)]\}}$$

where $\mu[t]$ = service rate of the lock in year t

μ_0 = service rate of the lock in year 0

a_3, b_3, c_3 = coefficients

Mfail[t] = mechanical device probability of failure in year t

GCI[t] = lock gate condition index in year t

WCI[t] = lock wall condition index in year t

Default values are as follows:

μ_0 = 2.0 tows/hr

a_3 = 8.0

b_3 = 1.0

c_3 = 1.0

312. The standard deviation of service time is computed as follows:

$$\sigma[t] = a_4 * \sigma_{GCI}[t]^2 + b_4 * \sigma_{WCI}[t]^2 + c_4 * Mfail[t]^2 \qquad (82)$$

where $\sigma[t]$ = standard deviation of service time in year t

a_4, b_4, c_4 = coefficients

$\sigma_{GCI}[t]$ = standard deviation of gate condition index in year t

$\sigma_{WCI}[t]$ = standard deviation of wall condition index in year t

Mfail[t] = mechanical device probability of failure in year t

Default values are as follows:

a_4 = 0.40

b_4 = 0.10

c_4 = 25

The user may edit the values of a_3, b_3, and c_3.

313. From these preliminary computations, average delays are computed as follows:

$$Wu = \begin{cases} \text{average delay from M/G/1 model} & \text{if } LD > 3 \text{ miles} \\ \text{average delay from G/G/1 model} & \text{if } LD < 3 \text{ miles} \end{cases}$$

$$Wd = \begin{cases} \text{average delay from M/G/1 model} & \text{if } LU > 3 \text{ miles} \\ \text{average delay from G/G/1 model} & \text{if } LU < 3 \text{ miles} \end{cases}$$

The specific equations for the M/G/1 and G/G/1 queuing models were described in Part IV.

314. The annual traffic delay D is computed as follows:

$$D = T[pu * Wu + (1-pu) * Wd] \qquad (83)$$

where pu is the fraction of total traffic through the lock that is heading upstream. The default value of pu is 0.50.

315. The user cost D_c for a given year is then computed as follows:

$$D_c = D * d_c \qquad (84)$$

The default value of d_c, the average tow delay cost per hour, is \$100.00/tow-hr. This value may be edited by the user.

316. Downtime Cost. The equations used to compute downtime cost, M_c, are as follows:

$$M_c = \frac{S \times 1}{365 \times T \times V} \tag{85}$$

$$S = S_s + S_{us} \tag{86}$$

$$S_s = \frac{\max\,(G_s,\ W_s,\ M_s)^2}{2} \tag{87}$$

$$S_{us} = \frac{L \times \Sigma\,(k \times \text{inc prob})^2}{2} \tag{88}$$

where M_c = the cost (in dollars per year) incurred by barge operators if the lock is taken out of service for scheduled or unscheduled REMR work

S_s = total waiting time in days for all the potentially arriving traffic during the scheduled REMR period

T = annual traffic in tons/yr

S_{us} = total waiting time in days for all the arriving traffic during the unscheduled REMR period

V = the average unit downtime cost incurred by barge operators, in dollars per tow per day

k = the average number of days needed to carry out an unscheduled REMR activity

inc_prob = incremental probability of failure as defined in Part III.

$$\text{Gs or Ws or Ms} = \begin{cases} \text{40 days, if a major rehabilitation is done in that year} \\ \text{5 days, if a minor rehabilitation is done in that year} \\ \text{0 days, otherwise} \end{cases}$$

The default value of k is 5 days. The default value of L is 24. The default value of V is $100.00, which may be edited by the user.

317. Cost Tallies. Once all the cost items are computed, the agency cost can be computed by summing the following items:

Scheduled Maintenance Cost for lock gates

Scheduled Maintenance Cost for lock walls

Scheduled Maintenance Cost for mechanical devices

Unscheduled Maintenance Cost for lock gates

Unscheduled Maintenance Cost for lock walls

Unscheduled Maintenance Cost for mechanical devices

Routine Maintenance Cost

Damage Cost

where all the cost items except damage cost are already described by Equations 77 through 89. Damage cost is taken as $15,320 per incident, but the user may edit that value.

318. The user cost can be computed by summing the Delay Cost and Downtime Cost.

319. The discounted agency cost is computed by using the following formula:

Discounted Agency Cost =

$$\sum_{i=1}^{\text{Planning Horizon}} \text{Agency cost } [i] * \exp \frac{(-\text{discount-rate} * i)}{100} \tag{89}$$

320. Similarly, the discounted user cost can be computed by using the following formula:

Discounted User Cost =

$$\sum_{i=1}^{\text{Planning Horizon}} \text{User Cost } [i] * \exp \frac{(-\text{discount-rate} * i)}{100} \tag{90}$$

321. The total cost is computed by summing up the agency and user cost:

Total_Cost[t] = Agency_Cost[t] + User_Cost[t]

Discounted Total_Cost = Discounted Agency Cost + Discounted User_Cost

Problem Description: Input and Editing of Data

322. The prototype REMR Management System has been developed as an interactive program for use on IBM PC and compatible machines. Communication with the system is through a series of menus displayed in windows on the screen. Other windows are used to display HELP files or subsidiary files containing additional details about a specific item of information. Three examples of screens used for input and editing of data are presented in this section.

Planning horizon and discount rate

323. The length of planning horizon can be defined from 1 year to 100 years, depending on the number of years the user wants to consider in life-cycle costing. The user should be careful in defining the length of the planning horizon. If a short period is selected, costs may not include major rehabilitations to a sufficient degree. On the other hand, a long planning horizon will exceed the limits of long-term projections. The default length of planning horizon is 50 years.

324. The discount rate is used to compute the total present dollar value of the annual agency and user costs. The default value is 8-1/8 percent.* Figure 49 shows the window that displays the planning horizon length and the discount rate. The user may edit these values by calling up this window on the screen and changing respective values using system EDIT commands.

Default values and coefficients

325. The technical relationships (Equations 70 through 91) refer to a set of initial conditions and coefficients. Many of the conditions and coefficients are assigned default values that may be modified by the user by calling up the window that displays the current value of the parameter and using the system EDIT commands. The specific details regarding the default values of those coefficients and initial conditions were discussed in the previous section. Examples of windows containing parameter values are given in the paragraphs below.

---

* Since this report was prepared, the rate used by the Corps of Engineers has increased to 8-7/8 percent.

```
planning horizon 50
base year        1986
discount rate    0.125
```

```
SELECT:     set run parameters    predict    opt
```

Figure 49. Window displaying planning horizon, base year, and discount rate

326. The right window of Figure 50 displays the following data:

a. The initial values of the condition indices for lock gates and walls.

b. Coefficients and values used in several of the equations discussed in the previous section, including the initial condition of lock gates and walls and coefficients used in Equation 71 to predict facility condition, the initial standard deviation used in Equation 73 to predict the standard deviation of future condition, parameters a and b needed to compute maintenance costs (corresponding, respectively, to coefficients a_6 and b_6 in Equation 77 and a_7 and b_7 in Equation 78), and unscheduled minor maintenance costs used in Equation 79.

c. Damage costs per incident used to determine the agency costs.

The data in Figure 50 are maintained in the system for each lock facility defined by the user. For any lock, the user may modify the values of any parameters shown in the window in Figure 50 using the EDIT commands.

327. The remaining set of technical data that can be controlled by the user are illustrated in the window reproduced in Figure 51. The items in

short name:	DASHI
name:	DAS
river:	OHI
mile marker	967
district:	ORP
division:	ORD
state:	OH
year open:	192
length:	600
width:	110
height:	18
main chamber?:	YES
lock up:	MON
lock down:	EMS
edit history:	
edit deterioration model:	
edit traffic/capacity model:	

gate	initial c.i.:	9.80
	coeff a:	0.10
	coeff b:	0.64
	sigma zero:	0.12
	maint a:	7689.00
	maint b:	1035116.00
	minor maint:	182355.00
wall	initial c.i.:	9.80
	coeff a:	0.10
	coeff b:	0.46
	sigma zero:	0.10
	maint a:	25462.00
	maint b:	1250190.00
	minor maint:	232260.00
mech	dev init fail prob:	0.005
	maint a:	7664.00
	maint b:	3406321.00
	minor maint:	175440.00
damage cost:		15320.00

Figure 50. Windows displaying parameters for facility condition

```
short name:                     DASHI
name:                           DASHIELDS
river:                          OHIO RIVER
mile marker                     967.70
district:                       ORP
division:                       ORD
state:                          OH
year open:                      1929
length:                         600
width:                          110
height:                         18
main chamber?:                  YES
lock up:                        NONE
lock down:                      NONE
edit history:
edit deterioration model:
edit traffic/capacity model:
```

```
traffic growth rate:     3.00
        growth years:    10.00
        growth start:    4000.00
s rate zero:             2.00
srate coefficient a:     -8.00
      coefficient b:     -1.00
      coefficient c:     -1.00
s sigma zero:            0.10
lockages / tow:          1.15
average lockage cost:    70.00
average delay cost:      100.00
upstream proportion:     0.50
closure cost:            100.00
```

Figure 51. Windows displaying traffic and service characteristics

Figure 51 relate to traffic and to the service characteristics of each lock and can be modified using the EDIT commands.

328. At the top of the right window in Figure 51 are data related to traffic volume and growth. The first parameter is the traffic growth rate expressed as an annual percentage. The second parameter, growth years, is the number of years for which the traffic growth described by Equation 70 will be computed. The initial traffic level in tows per year is indicated by the variable assigned to "growth start." Explanations of these variables are given with Equation 70 and in Figure 48.

329. Parameters related to the operational characteristics of each lock are also shown in Figure 51. These data include the following:

a. The initial service rate in tows/hr and the coefficients used to compute the service rate in Equation 82.

b. the initial value of the standard deviation of service time (used in Equation 83 but not implemented in the prototype model).

c. the lockages per tow (i.e., the annual average number of lockage cycles per tow), related both to average number of barges per tow and the dimensions of the lock.

d. the average lockage cost, used in Equation 80 to compute operating costs.

e. the average delay cost, or the cost (in dollars per tow per hour) incurred by each tow due to the time spent waiting in the queue and being serviced in the lock.

f. the upstream proportion, or the ratio of upstream traffic to total traffic in a year (essentially, a measure of the directionality of the total traffic at a lock).

g. the closure cost, or the penalty (in dollars per tow per hour) due to expected closure of the lock to perform REMR activities.

REMR policies

330. The prototype Management System provides three ways, or schemes, for users to specify REMR policies. These schemes are illustrated in Figure 52 and are intended to reflect the different ways in which the several REMR classes of activities (i.e., routine maintenance and evaluation, repair, and rehabilitation) interact with one another. For example, Scheme 1 at the top of Figure 52 illustrates the case where emphasis is placed on major rehabilitation to restore facility condition once the condition index has reached the threshold quality standard. Minor rehabilitation and repairs are carried out, but only as part of a periodic maintenance and repair effort.

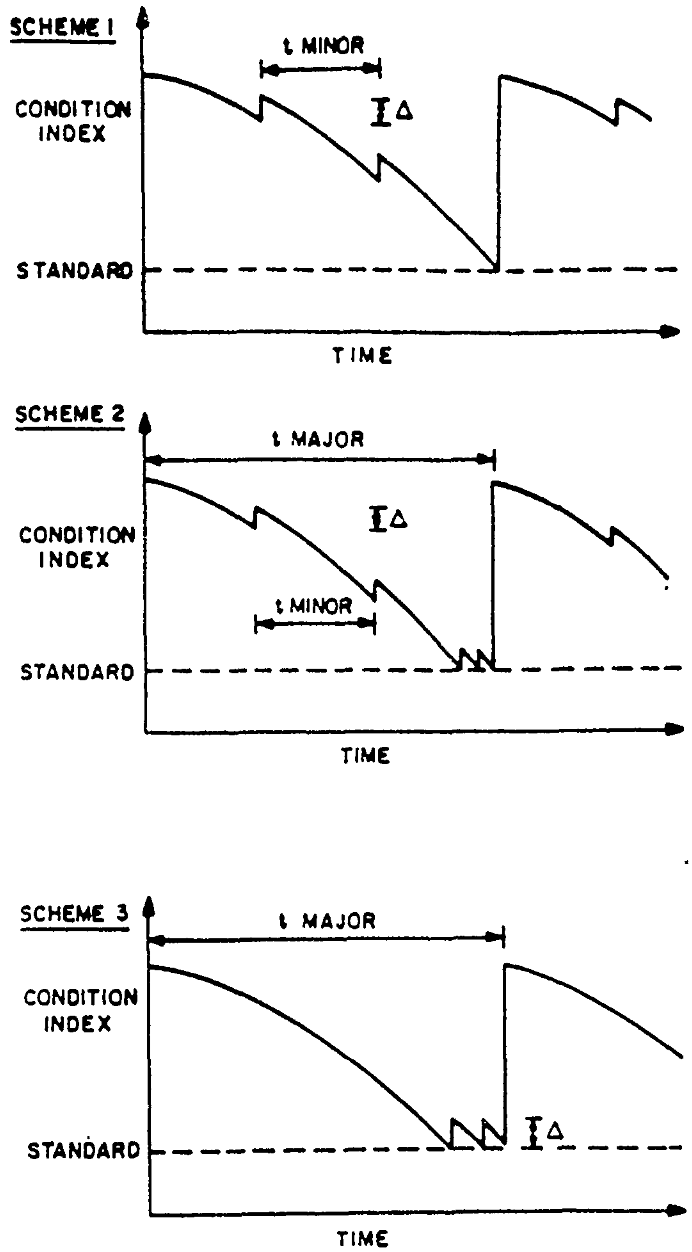


Figure 52. Three different methods to define REMR activities

331. Schemes 2 and 3 do not call for rehabilitation when the condition index reaches the threshold standard, but rather employ rehabilitation or repair only on a scheduled basis. To keep the facility functioning at standard until rehabilitation can be performed, the system assumes a series of minor rehabilitations or repairs. Scheme 2 differs from Scheme 3 in that it

also permits repairs to be performed during the course of the facility's life. These two schemes are thus useful if major capital expenditures are better assessed on a "scheduled" rather than a "responsive" basis.

332. Within each of these schemes, different policies may be expressed, either by specifying the timing of different REMR actions or by controlling the degree of improvement in facility condition with the performance of each activity. The sensitivity of projections of facility performance and cost to variations in REMR policy will be illustrated in the following section.

Example Runs

333. This section presents examples of the prototype REMR Management System and illustrates the structure and interpretation of its results. For simplicity in explaining the results and drawing comparisons, all REMR policies will be expressed using Scheme 2 in Figure 52.

REMR policy input

334. Figure 53 contains windows describing a REMR policy using Scheme 2.* The user selections in Figure 53 specify the following information for lock gates, walls, and mechanical equipment:

- a. The REMR policy name (to identify this policy in the Management System).
- b. The REMR policy number (to identify different policies used in different runs).
- c. The condition index standard (e.g., 4.1 for lock gates). This input corresponds to parameter Q_1 or Q_2 in Figure 23.
- d. The major rehabilitation interval, time major, in years (e.g., 45 years for lock gates). This input corresponds to parameter t_1 or t_2 in Figure 23, and is illustrated directly in Figure 52.
- e. The minor rehabilitation interval, time minor, in years (e.g., 30 years for lock gates). This input represents the time interval in years between two succeeding minor rehabilitations or repairs (see Figure 52).
- f. The amount of improvement in the condition index, Δ, due to a minor rehabilitation (e.g., 0.45 for lock gates). This input

* Refer to Figures 15, 23, and 24 for the concepts and terms used to represent REMR policy analytically.

corresponds to the parameter I_1 in Figure 24,* and is also shown in Figure 52.

g. The routine maintenance level on a scale of 0 to 10 (e.g., 4.0 for lock gates). The routine maintenance level is shown on the right window of Figure 53. To call up this window, the user moves the cursor to "routine maintenance level:" on the left menu and presses RETURN. The user can vary the routine maintenance level up to four times during the planning horizon. For purposes of this example, the same routine maintenance levels will be used throughout the planning horizon. These inputs of routine maintenance level correspond to the variable Routine[t], used to compute parameter δ in Equations 7 and 73.

335. This information is entered by the user for lock gates, walls, and mechanical equipment. For mechanical equipment, the user can define only one routine maintenance level for the entire planning horizon. For gates and walls, the effect of routine maintenance is reflected in the variance of the condition index; for mechanical equipment, it is reflected by changes in the slope of the curve in Figure 21 (similar to the variation shown in Figure 13, Part II). Finally, the inputs and internal calculations related to mechanical equipment condition are in terms of probability of failure (on a 0 to 1 scale). When results are displayed, this probability will be converted to an equivalent measure of condition (0 to 10 scale) by multiplying the probabilities of failure by 10.

336. The user can also change the basic parameters of the economic analysis, such as planning horizon and discount rates. This is done by calling up the window in Figure 49. For the example run, the default planning horizon (50 years) and the default discount rate (8-1/8 percent) were used.

337. To begin the analysis, select menu option RUN, then option PREDICT. When the Management System has completed its analysis, the user should select the menu option REPORT to display the results on the screen. Figures 54, 55, 56, and 57 display the several categories of results obtained for the REMR policy described above. The interpretation and use of each of these results will be described in turn.

---

* Note: For mechanical equipment the value of Δ is input in units of probability of failure (0-1), rather than condition index (0-10). Therefore, the value of 0.024 shown in Figure 53 is equivalent to a value of 0.24 on a condition index scale.

name:	P1
number:	5
gate cond index std:	4.10
time major:	45.00
time minor:	30.00
delta:	0.45
routine maint levels:	
wall cond index std:	8.00
time major:	45.00
time minor:	30.00
delta:	0.20
routine maint levels:	
mech dev cond index std:	0.134
time major:	20.00
time minor:	11.00
delta:	0.024
routine maint level:	4.00

ROUTINE MAINTAINENCE
Year 1986 Level 4.00
Year 0 Level 0.00
Year 0 Level 0.00
Year 0 Level 0.00

Figure 53. Windows describing a REMR policy using Scheme 2

Condition reports

338. Figure 54 displays the condition of the facility throughout the planning horizon. Results displayed for gates and walls include the respective policy of routine maintenance, the expected value of condition index, and the standard deviation of condition index for each year in the analysis period. For mechanical equipment, the results include the expected value of the condition index (the probability of failure multiplied by 10).

339. The condition of each facility component deteriorates in this simulation until a REMR activity is performed. For example, in the 30th year (i.e., 2015), a minor rehabilitation is performed on gates and walls; therefore, the expected value of the condition index of lock gates is increased by Δ (0.45), and the standard deviation of the condition index is decreasd to 75 percent of the level in the preceding year. Similarly, the expected condition of walls increases by 0.20, and the standard deviation of condition is decreased accordingly.

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
1986	4.00	9.70	0.13	4.00	9.70	0.10	9.95
1987	4.00	9.61	0.13	4.00	9.64	0.11	9.89
1988	4.00	9.55	0.14	4.00	9.61	0.12	9.84
1989	4.00	9.50	0.15	4.00	9.58	0.12	9.80
1990	4.00	9.44	0.15	4.00	9.55	0.13	9.75
1991	4.00	9.38	0.16	4.00	9.52	0.13	9.70
1992	4.00	9.32	0.17	4.00	9.49	0.14	9.64
1993	4.00	9.26	0.18	4.00	9.46	0.15	9.58
1994	4.00	9.19	0.18	4.00	9.43	0.15	9.51
1995	4.00	9.12	0.19	4.00	9.40	0.16	9.44

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
1996	4.00	9.04	0.20	4.00	9.37	0.17	9.68
1997	4.00	8.96	0.21	4.00	9.34	0.18	9.64
1998	4.00	8.88	0.22	4.00	9.31	0.19	9.58
1999	4.00	8.80	0.23	4.00	9.27	0.19	9.51
2000	4.00	8.70	0.25	4.00	9.24	0.20	9.44
2001	4.00	8.61	0.26	4.00	9.21	0.21	9.37
2002	4.00	8.51	0.27	4.00	9.17	0.22	9.28
2003	4.00	8.40	0.28	4.00	9.13	0.24	9.19
2004	4.00	8.29	0.30	4.00	9.10	0.25	9.09
2005	4.00	8.17	0.31	4.00	9.06	0.26	9.95

----- PRESS A KEY FOR MORE -----

Figure 54. Facility Condition Report for a REMR policy (Policy 5 of Figure 58) using Scheme 2 (Continued)

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
2006	4.00	8.05	0.33	4.00	9.02	0.27	9.89
2007	4.00	7.92	0.34	4.00	8.98	0.29	9.84
2008	4.00	7.79	0.36	4.00	8.93	0.30	9.80
2009	4.00	7.65	0.38	4.00	8.89	0.31	9.75
2010	4.00	7.50	0.39	4.00	8.85	0.33	9.70
2011	4.00	7.35	0.41	4.00	8.80	0.35	9.64
2012	4.00	7.19	0.43	4.00	8.76	0.36	9.58
2013	4.00	7.02	0.46	4.00	8.71	0.38	9.51
2014	4.00	6.84	0.48	4.00	8.66	0.40	9.44
2015	4.00	7.29	0.36	4.00	8.86	0.30	9.37

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
2016	4.00	7.19	0.38	4.00	8.80	0.31	9.61
2017	4.00	7.02	0.39	4.00	8.76	0.33	9.51
2018	4.00	6.84	0.41	4.00	8.71	0.34	9.44
2019	4.00	6.66	0.43	4.00	8.66	0.36	9.37
2020	4.00	6.47	0.45	4.00	8.61	0.38	9.28
2021	4.00	6.27	0.48	4.00	8.56	0.40	9.19
2022	4.00	6.06	0.50	4.00	8.50	0.42	9.09
2023	4.00	5.85	0.52	4.00	8.45	0.44	8.99
2024	4.00	5.62	0.55	4.00	8.40	0.46	8.88
2025	4.00	5.39	0.58	4.00	8.34	0.48	9.95

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
2026	4.00	5.15	0.61	4.00	8.28	0.50	9.89
2027	4.00	4.89	0.63	4.00	8.22	0.53	9.84
2028	4.00	4.63	0.67	4.00	8.16	0.55	9.80
2029	4.00	4.36	0.70	4.00	8.10	0.58	9.75
2030	4.00	9.80	0.12	4.00	9.80	0.10	9.70
2031	4.00	9.61	0.13	4.00	9.64	0.10	9.64
2032	4.00	9.55	0.13	4.00	9.61	0.11	9.58
2033	4.00	9.50	0.14	4.00	9.58	0.12	9.51
2034	4.00	9.44	0.15	4.00	9.55	0.12	9.44
2035	4.00	9.38	0.15	4.00	9.52	0.13	9.37
AVE.	4.00	7.89	0.32	4.00	9.05	0.27	9.56

----- PRESS A KEY FOR MORE -----

Figure 54. Facility Condition Report for a REMR policy (Policy 5 of Figure 58) using Scheme 2 (Concluded)

340. Major rehabilitations of lock gates and walls is scheduled every 45 years (i.e., 2030 within this analysis period). In these years, the expected values of the condition index for these components are restored to their as-built states (i.e., 9.80). Similarly, the standard deviation of the condition index is also brought down to its initial level (i.e., 0.12). After the major rehabilitation, the condition of the gates and walls begins to deteriorate again.

341. For mechanical equipment, note that minor rehabilitation is scheduled to be performed every 11 years, and a major rehabilitation every 20 years. Therefore, the condition index improves from 9.44 to 9.68 in 1996, from 9.37 to 9.61 in 2016, due to the minor rehabilitations, and is restored to 9.95 in 2005, 2025, and so on, due to the major rehabilitations or overhauls.

342. The last row of the facility condition report displays the time-average values of the facility condition over the planning horizon. For example, the time-average value of the condition index of lock gates through 50 years is 7.89, and the average value of the standard deviation of the condition index of lock gates is 0.32. Corresponding values are displayed for the lock walls and mechanical equipment.

<u>Traffic and service parameters</u>

343. Figure 55 displays the predicted service parameters of the facility. These parameters are used to compute user costs. The last column of the figure lists the predicted average tow delays (hr/tow) for each year. Both the service rate and its standard deviation (and therefore the average tow delay) deteriorate with declining condition of the facility and are improved somewhat in the years in which REMR activities are performed. It is in these calculations, therefore, that the impacts of REMR policies to users are directly accounted for. The last row of Figure 55 displays the time-average of service parameter values over the planning horizon.

<u>REMR costs</u>

344. Figure 56 tabulates the costs predicted for maintaining the facility under the REMR policy defined in Figure 53. Results are organized as follows:

- a. Column 1 identifies the simulated year of the analysis period.
- b. Columns 2 through 4 show the annual costs for repair and rehabilitation for gates, walls, and mechanical equipment,

MANAGEMENT SYSTEM FOR CIVIL WORKS   PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
1986	4249.37	1.95	0.18	0.00	0.62
1987	4453.53	1.94	0.25	0.00	0.65
1988	4620.68	1.94	0.29	0.00	0.67
1989	4757.54	1.94	0.33	0.00	0.69
1990	4869.59	1.93	0.37	0.00	0.71
1991	4961.32	1.93	0.40	0.00	0.74
1992	5036.43	1.93	0.44	0.00	0.76
1993	5097.92	1.93	0.47	0.00	0.79
1994	5148.27	1.92	0.51	0.00	0.82
1995	5189.49	1.92	0.54	0.00	0.85

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
1996	5223.24	1.92	0.42	5.00	0.76
1997	5250.87	1.92	0.44	0.00	0.78
1998	5273.49	1.91	0.48	0.00	0.81
1999	5292.01	1.91	0.51	0.00	0.84
2000	5307.18	1.90	0.55	0.00	0.87
2001	5319.59	1.90	0.58	0.00	0.90
2002	5329.75	1.89	0.62	0.00	0.94
2003	5338.08	1.88	0.66	0.00	0.98
2004	5344.89	1.87	0.70	0.00	1.02
2005	5350.47	1.89	0.25	40.00	0.70

----- PRESS A KEY FOR MORE -----

Figure 55. Facility Service Report for a REMR policy (Policy 5 of Figure 58) using Scheme 2 (Continued)

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2006	5355.04	1.88	0.31	0.00	0.73
2007	5358.78	1.87	0.35	0.00	0.76
2008	5361.84	1.86	0.38	0.00	0.78
2009	5364.34	1.84	0.42	0.00	0.81
2010	5366.40	1.83	0.46	0.00	0.84
2011	5368.08	1.81	0.49	0.00	0.88
2012	5369.45	1.78	0.53	0.00	0.92
2013	5370.58	1.76	0.57	0.00	0.97
2014	5371.50	1.73	0.60	0.00	1.02
2015	5372.26	1.79	0.60	5.00	0.98

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2016	5372.87	1.79	0.50	5.00	0.90
2017	5373.38	1.76	0.55	0.00	0.95
2018	5373.79	1.73	0.58	0.00	1.00
2019	5374.13	1.69	0.62	0.00	1.06
2020	5374.41	1.65	0.66	0.00	1.13
2021	5374.64	1.60	0.70	0.00	1.22
2022	5374.82	1.54	0.74	0.00	1.31
2023	5374.98	1.48	0.78	0.00	1.44
2024	5375.10	1.40	0.82	0.00	1.59
2025	5375.20	1.35	0.38	40.00	1.19

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2026	5375.29	1.26	0.44	0.00	1.36
2027	5375.36	1.17	0.48	0.00	1.57
2028	5375.41	1.08	0.51	0.00	1.85
2029	5375.46	0.98	0.55	0.00	2.26
2030	5375.50	1.94	0.40	40.00	0.75
2031	5375.53	1.94	0.43	0.00	0.77
2032	5375.55	1.93	0.46	0.00	0.80
2033	5375.57	1.93	0.50	0.00	0.82
2034	5375.59	1.93	0.54	0.00	0.85
2035	5375.60	1.92	0.57	0.00	0.88
AVE.	5251.40	1.77	0.50	3.60	0.97

Total expected but unscheduled down time is 1.37 days

----- PRESS A KEY FOR MORE -----

Figure 55. (Concluded)

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	gate rep	wall rep	mech rep	routine rep	damage	total
1986	0	0	0	21	15	37
1987	0	0	1	21	15	38
1988	0	0	1	21	15	37
1989	0	0	1	21	15	37
1990	0	0	1	21	15	38
1991	0	0	1	21	15	38
1992	0	0	1	21	15	38
1993	0	0	1	21	15	38
1994	0	0	1	21	15	38
1995	0	0	1	21	15	38

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
1996	0	0	147	21	15	184
1997	0	0	0	21	15	37
1998	0	0	1	21	15	38
1999	0	0	1	21	15	38
2000	0	0	1	21	15	38
2001	0	0	1	21	15	38
2002	0	0	1	21	15	38
2003	0	0	2	21	15	38
2004	0	0	2	21	15	38
2005	0	0	349	21	15	386

----- PRESS A KEY FOR MORE -----

Figure 56. Facility Cost Report for a REMR policy
(Policy 5 of Figure 38) using Scheme 2 (Continued)

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2006	0	0	0	21	15	37
2007	0	0	1	21	15	37
2008	0	0	1	21	15	37
2009	0	0	1	21	15	38
2010	0	0	1	21	15	38
2011	0	0	1	21	15	38
2012	0	0	1	21	15	38
2013	0	0	1	21	15	38
2014	0	0	1	21	15	38
2015	780	454	1	21	15	1272

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2016	0	0	147	21	15	184
2017	0	0	0	21	15	37
2018	0	0	1	21	15	38
2019	0	0	1	21	15	38
2020	0	0	1	21	15	38
2021	0	0	2	21	15	38
2022	0	0	2	21	15	38
2023	0	0	2	21	15	38
2024	0	0	2	21	15	39
2025	0	0	404	21	15	441

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2026	0	0	0	21	15	37
2027	0	0	1	21	15	37
2028	0	0	1	21	15	37
2029	0	0	1	21	15	38
2030	5923	3595	1	21	15	9556
2031	0	0	1	21	15	38
2032	0	0	1	21	15	38
2033	0	0	1	21	15	38
2034	0	0	1	21	15	38
2035	0	0	1	21	15	38
EUC.	18	11	14	21	15	78
TOT.	221	133	167	248	178	946

Discount rate = 8.125%   Costs are in thousands of dollars

----- PRESS A KEY FOR MORE -----

Figure 56. (Concluded)

respectively. These costs are for both scheduled and unscheduled activities.

c. Column 5 displays the annual costs of routine maintenance for the facility overall.

d. Column 6 gives the annual costs to repair damage due to barges.

e. Column 7 sums the costs in Columns 2 through 6 (some round-off error may be observed).

345. To interpret these data, consider the example of lock gates. Since REMR activities for gates are performed 30 and 45 years into the planning horizon (i.e., 2015 and 2030), the scheduled REMR costs in those years are nonzero. Within a cost stream, these costs represent the "spikes" shown conceptually in Figure 16. Although the repair and rehabilitation costs for lock gates in other years are zero in Figure 56, they do not have to be.

346. Unscheduled repair costs may occur if the incremental probability of the condition index falling below 1.5 were significant. In the example in Figure 56, there were no unscheduled REMR costs for gates because the condition of the lock gates remained fairly high throughout the analysis period. The pattern of projected cost expenditures for walls is similar to that for gates, as would be expected from the similarity of the policy specifications in Figure 53.

347. A somewhat different pattern occurs with mechanical equipment. Besides periodically scheduled REMR cost requirements, we also see small amounts of unscheduled REMR costs for mechanical equipment. These latter costs arise from the frequency with which mechanical equipment is assumed to fail.

348. The fifth and sixth columns in Figure 56 display the predicted routine maintenance and damage costs, respectively. These costs constitute the curve "Cost of Maintenance" in Figure 16. Since the level of routine maintenance is constant throughout the analysis period, the routine maintenance expenditures (in real dollars) are also constant. As described in Part III, the frequency of damage due to moving barges fits a Poisson distribution; therefore, the damage cost remains constant in every year.

349. These cost predictions are tallied in two ways at the bottom of Figure 56. The second to the last row in Figure 56 displays the equivalent uniform annual cost (EUC) for the corresponding columns. The last row of Figure 56 displays the discounted sum of the costs of each column. The total

discounted agency costs (excluding operating costs) for the facility over the 50-year period are $946,000. This discounted total cost represents one point in the curve "Costs To Facility Agency" of Figure 18.

Total cost summaries

350. Figure 57 displays the agency, user, and total costs for the entire planning horizon. Agency costs are taken directly from the annual totals in Figure 56. User costs are computed from the annual service statistics in Figure 55. User costs increase with time, a reflection of the lower service and longer delays of a somewhat more deteriorated facility. When a scheduled REMR activity is performed for any of the components, however, the average condition of the facility improves, also restoring some measure of the quality and reliability of service provided the barge traffic. This impact of REMR is reflected as a decrease in user costs from the previous year or as an effective increase in user benefit.

351. The equivalent uniform annual costs and the total discounted costs for each column are displayed at the bottom of Figure 57. The discounted sum of the user costs represents one point in the curve "Impacts: Reductions In Costs" of Figure 18. Similarly, the discounted sum of the total costs represents one point in the curve "Total Costs" of Figure 18.

352. These discounted cost totals are important, in that they form the basis for evaluating REMR policy. In particular, managers would like to identify that REMR policy that minimizes the sum of the agency and user costs, and therefore provides the most efficient level of water transportation. Recognizing that different REMR policies yield different REMR requirements, costs, and impacts, it is necessary to repeat the process above for REMR policies based upon different frequencies and standards of work. The objective is to identify an optimal REMR policy that is analogous to the policy P* of Figure 18.

Analysis of competing REMR policies

353. In addition to the REMR policy described above, five other REMR policies were defined. They vary from high to low standard as suggested in Figure 18. Policy 5 and its costs and impacts were just described above. This policy was defined in Figure 53. The definitions of other REMR policies (Policies 1, 2, 3, 4, and 6) and their corresponding results are included in Appendix C. A summary of the results for all six REMR policies is shown in Figure 58. This summary will be sufficient for the following discussion.

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	agency cost	user cost	total cost
1986	37	265	302
1987	38	290	328
1988	37	311	348
1989	37	331	368
1990	38	349	387
1991	38	368	406
1992	38	386	424
1993	38	404	442
1994	38	423	461
1995	38	442	480

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
1996	184	418	602
1997	37	412	449
1998	38	428	466
1999	38	445	483
2000	38	463	501
2001	38	482	520
2002	38	503	541
2003	38	525	563
2004	38	549	587
2005	386	1549	1935

----- PRESS A KEY FOR MORE -----

Figure 57. Facility Total Cost Report for a REMR policy (Policy 5 of Figure 58) using Scheme 2 (Continued)

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2006	37	393	430
2007	37	406	443
2008	37	421	458
2009	38	436	474
2010	38	454	492
2011	38	473	511
2012	38	495	533
2013	38	520	558
2014	38	549	587
2015	1272	546	1818

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2016	184	501	685
2017	37	512	549
2018	38	540	578
2019	38	572	610
2020	38	610	648
2021	38	655	693
2022	38	708	746
2023	38	773	811
2024	39	854	893
2025	441	1818	2259

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2026	37	730	767
2027	37	843	880
2028	37	998	1035
2029	38	1218	1256
2030	9556	1582	11138
2031	38	416	454
2032	38	429	467
2033	38	443	481
2034	38	459	497
2035	38	475	513
EUC.	78	416	494
TOT.	946	5012	5958

Discount rate = 8.125%   Costs are in thousands of dollars

----- PRESS A KEY FOR MORE -----

Figure 57. (Concluded)

LOCK MAINTENANCE MANAGEMENT SYSTEM
COMPUTER RUN SUMMARY REPORT
ACROSS DIFFERENT REMR POLICIES

	HIGH					LOW
INPUT:	POLICY 1	POLICY 2	POLICY 3	POLICY 4	POLICY 5	POLICY 6
LOCKGATES:						
Condition Standard:	8.8	7.6	6.7	5.4	4.1	2.1
Major Rehab Interval:	25	30	35	40	45	49
Repair Interval:	10	15	20	25	30	35
Routine Maint Level:	8	7	6	5	4	3
Repair Delta CI:	0.45	0.45	0.45	0.45	0.45	0.45
LOCKWALLS:						
Condition Standard:	9.2	8.9	8.7	8.4	8	7.7
Major Rehab Interval:	25	30	35	40	45	49
Repair Interval:	10	15	20	25	30	35
Routine Maint Level:	8	7	6	5	4	3
Repair Delta CI:	0.2	0.2	0.2	0.2	0.2	0.2
MECH. EQUIPMENT:						
Prob fail Standard:	0.055	0.064	0.084	0.107	0.134	0.184
Major Rehab Interval:	14	15	16	18	20	22
Repair Interval:	7	8	9	10	11	12
Routine Maint Level:	8	7	6	5	4	3
Repair Delta PFAIL:	0.024	0.024	0.024	0.024	0.024	0.024
OUTPUT:						
AVERAGES:						
Lockgate CI:	9.37	9.03	8.75	8.39	7.89	7.28
Lockwall CI:	9.52	9.39	9.31	9.2	9.05	8.89
Mech Equip CI:	9.82	9.78	9.73	9.65	9.56	9.46
Serv. Rate(Tows/Hr.):	1.93	1.92	1.9	1.86	1.77	1.64
Delay (Hrs/Tow):	0.7	0.72	0.75	0.82	0.97	1.73
ANNUAL DOWNTIMES:						
Scheduled (Days):	6.8	4.7	4.5	3.7	3.6	3.6
Unscheduled (Days):	0.73	0.84	0.94	1.14	1.37	2.04
DISCOUNTED COSTS: (in thousand dollars)						
Lockgates:	$783	$485	$367	$287	$221	$182
Lockwalls:	$563	$346	$242	$179	$133	$101
Mech Equipment:	$212	$199	$190	$178	$167	$166
Routine Maintenance:	$939	$723	$536	$377	$248	$147
Damage Costs:	$178	$178	$178	$178	$178	$178
Agency: Total:	$2,675	$1,931	$1,512	$1,199	$946	$774
Equiv Unif Cost:	$222	$160	$125	$99	$78	$64
User: Total:	$4,761	$4,601	$4,752	$4,831	$5,012	$5,655
Equiv Unif Cost:	$395	$381	$394	$401	$416	$469
Total:	$7,436	$6,531	$6,264	$6,030	$5,958	$6,429

Figure 58. Summary of results from different REMR policy inputs

354. The comparison of the six policies and the implications of these results for decisions on the optimal policy to pursue may be concisely stated as follows:

a. The policies are ordered such that the standards of REMR decrease from left to right. As the REMR standard decreases, the amount of REMR activities performed to the facility also decreases. Therefore, moving from higher to lower REMR policy standard (i.e., from Policy 1 to Policy 6), the average condition and thus the service rate of the facility decreases. Since the service rate of the facility decreases, the average delay in service per tow increases.

b. The varying REMR requirements among Policies 1 through 6 have a direct effect on agency costs. With decreasing REMR requirements from Policy 1 to Policy 6, the discounted REMR cost requirements for lock gates, lock walls, mechanical equipment, and routine maintenance also decrease. This trend validates the shape of the curve "Costs To Facility Agency" in Figure 18.

c. While the average annual scheduled downtime decreases in Figure 58 from Policy 1 to Policy 6, the unscheduled downtime increases. This trade-off is a direct result of the lower condition of facility that results from the decreasing level of REMR. With the lower condition, the likelihood that any component will fail in any given year (thus, the likelihood of requiring an unscheduled REMR activity) increases.

d. From Policy 1 to Policy 6, the total discounted user cost decreases at first and then increases afterwards. This trend suggests that the shape of the curve "Impacts: Reductions In Costs" in Figure 18 may be convex, with a well-defined minimum. The reason for this behavior is that user costs consist of congestion costs due to waiting in queue plus the time needed to service the tow, and delay costs when the lock is closed for REMR. When the REMR policy standard is high, there are frequent and long-duration shutdowns for performing REMR. Therefore, the downtime cost is high relative to that of tow service and waiting in queue. When REMR policy standard is low, there is little downtime; however, the facility deteriorates more rapidly, and the level of service (affecting tow service time and delays in the queue) is worse, increasing the congestion costs. At some happy medium between these two conflicting trends, the total user costs are minimum.

e. The sum of the total discounted costs in Figure 58 indicates the relative economic worth of each policy. The policy for which this cost is minimum is the economically preferred policy. From Figure 58, this minimum occurs at Policy 5. Furthermore, the trend in total discounted costs among Policies 1 through 6 validates the shape of the curve "Total Costs" in Figure 18. In a discrete sense, Policy 5 corresponds to the optimal policy P* in Figure 18. Of course, more detailed

analyses could be made to "fine tune" this projection (e.g., using additional policies in the region between Policies 4 and 6) to identify perhaps more favorable policies. Nevertheless, the comparison among competing policies in Figure 58 serves to illustrate the basic ideas and procedures involved. More fundamentally, it provides a practical example of the application of demand-responsive concepts of REMR management discussed in Part II.

PART VI: SUMMARY AND RECOMMENDATIONS

355. The objective of this research program is to design, develop, and implement a computerized package to assist districts, divisions, and HQUSACE in managing REMR programs for civil works. This REMR Management System is based on the concepts outlined in Part II involving life-cycle costing of civil facilities and demand-responsive analyses of repair, evaluation, maintenance, and rehabilitation. Although the system embodies these innovative approaches to management, it seeks to conform as closely as possible with procedures of data collection and analysis, and of management and budgeting currently practiced by the Corps.

356. This report has addressed the conceptual design of the REMR Management System. Available mathematical techniques were investigated and appropriate models derived. A prototypical REMR Management System and its application were illustrated using locks.

357. Part I discussed the need for REMR activities, and the importance of managing REMR programs effectively in the future. Part II formulated the concepts needed to manage REMR programs, integrated different management elements within a framework of life-cycle facility costing, and identified analytic requirements to fulfilling such an approach. Part III reviewed available information on the frequency and costs of REMR performance, and developed indices and models of facility condition and of models of REMR costs. Part IV reviewed available information on assessment of benefits of civil works projects and developed models to predict the consequences of REMR activities. Part V developed a prototype REMR Management System, illustrated its use, and interpreted the results.

358. The Management System developed under this project is to be used on microcomputers. This strategy not only keeps pace with the growing popularity of microcomputer technology, but also attempts to exploit the unique and very attractive characteristics of these machines.

359. Results of this research indicate several areas where additional studies are recommended. The more prominent topics requiring investigation are the listed below.

- a. The mechanisms of deterioration affecting civil works, and the role of REMR activities in correcting or preventing distress need to be better understood.

b. Appropriate condition indices at the facility level need to be determined.

c. REMR standards and policies need to be quantified in terms of the type, extent, frequency, and quality of work performed.

d. Relationships quantifying the impacts or consequences of alternative REMR policies need to be determined.

e. Mathematical procedures to yield optimal REMR policies need to be identified.

f. Procedures to incorporate nonmonetary impacts (e.g., defense mobilization) into the decision structure need to be defined.

360. All of these topics present a challenge in their reduction within an analytic model. Nevertheless, the value of this approach for the REMR program was highlighted in Part I. The fact that analogous relationships have already been developed in management systems for other facilities suggests that a viable system can also be developed for Corps civil works structures.

REFERENCES

A'bin, Susan L., and Kai, Sheng Roan. 1986. Naval Research Logistics Quarter_', Vol 33, pp 120-143.

Antle, L. George, Sharp, F. M., and Goiocoechea, A. Draft. "Review of Risk Benefit Analysis in Lock and Dam Rehabilitation," Institute for Water Resources, US Army Corps of Engineers, Fort Belvoir, Va.

Balta, Wayne S. 1984 (Jun). "Optimal Investment Policies for Maintenance and Rehabilitation of Highway Pavements, M.S. thesis, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Mass.

Ben-Akiva and Lerman. 1985. Discrete Choice Analysis: Theory and Application to Travel Demand, Massachusetts Institute of Technology Press, Cambridge, Mass.

Berger, Louis, and Associates, Inc. 1981. "Engineering Analyses of Waterways Systems," Final Report US Army Corps of Engineers (part of National Waterways Study).

Box, G. E. P., and Jenkins, G. M. 1976. Time Series Analysis, Holden-Day, Inc.

DeSalvo, J. 1968. "Linehaul Process Functions for Rail and Inland Waterway Transportation," Ph.D dissertation, Northwestern University, Evanston, Ill.

Drake, A. 1967. Fundamentals of Applied Probability Theory, McGraw-Hill Book Company.

Engineer Regulation (ER) 500-1-18. 1985 (30 Mar). Corps of Engineers Continuity of Operations Planning System (CECOPS), Department of the Army, Office of the Chief of Engineers.

Engineer Regulation (ER) 1130-2-303. 1967 (15 Dec). Project Operation, Maintenance Guide, Department of the Army, Office of the Chief of Engineers.

Federal Register, Vol. 44, No. 242, 18 CFR Part 713, Section 1, December 14, 1979.

Fernandez-Larranaga, J. E. 1979 (Jun). "Optimal Dynamic Investment Policies for Public Facilities: The Transportation Case," Ph.D dissertation, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Mass.

Fernandez, J. E., and Friesz, T. L. 1981 (Feb). "Influence of Demand-Quality Interrelationships on Optimal Policies for Stage Construction of Transportation Facilities," Transportation Science, Vol 15, No. 1, pp 16-31.

Framji and Mahajan. 1969. Irrigation and Drainage in the World, International Commission on Irrigation and Drainage, New Delhi, India.

Friesz, T. L., and Fernandez, J. E. 1979 (May). "A Model of Optimal Transport Maintenance with Demand-Responsiveness," Transportation Research, Vol 13B, No. 4, pp 317-339.

Glassey, Roger C., and Ross, Sheldon M. 1976 (Nov). "Queuing Models for Multiple Chamber Locks," Transportation Science, Vol 10, No. 4.

Hochstein, A., Patton, R., and Louis Berger and Associates. 1981. "Engineering Analysis of the Waterways System, National Waterways Study," Institute for Water Resources, US Army Corps of Engineers, Fort Belvoir, Va.

Howe, Charles, et al. 1969. Inland Waterway Transportation Studies in Public and Private Management and Investment Decisions, Resources for the Future, Inc., Baltimore and London.

Institute of Civil Engineering. 1978. Floods and Reservoir Safety, London.

Lave, Lester B., and DeSalvo, Joseph S. 1976. "Congestion, Tolls, and the Economic Capacity of a Waterway," Journal of Political Economy.

Lovesky, Gary A. 1986 (May). "Development of a Knowledge Based System for the Condition Evaluation of Lock Gates," M.S. thesis, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Mass.

Markow, Michael J., and Brademeyer, Brian D. 1981 (Jun). "Modification of System EAROMAR: Final Technical Report," Federal Highway Administration, Washington, DC.

Markow, Michael J., et al. 1984 (Jun). "Intercity Transportation in Egypt: Summary Technical Report," Massachusetts Institute of Technology, Cambridge, Mass.

Markow, Michael J. 1982a. "Economically Efficient Pavement Design and Rehabilitation Policies Under High Traffic Volumes," Proceedings, Tenth Annual Meeting of the PTRC, London.

Markow, Michael J., et al. 1982 (Oct). Analysis of Track Maintenance and Rehabilitation Policy, prepared for the Red Nacional de los Ferrocarriles Espanoles (RENFE), MIT Center for Construction Research and Education, Cambridge, Mass.

Markow, Michael J. 1984 (Apr). "Planning and Management Alternatives in Rehabilitation of a National Rail System," Organizing and Managing Construction, Proceedings of the 4th International Symposium on Organization and Management of Construction, Vol 3 (Research), International Council for Building Research Studies and Documentation, University of Waterloo, Canada.

Markow, Michael J. 1978 (Dec). "Demand-Responsive Highway Maintenance Budgeting: A Report on the Massachusetts Maintenance Management System," prepared for Byrd, Tallamy, MacDonald and Lewis and the Commonwealth of Massachusetts, Cambridge, Mass.

Markow, Michael J. 1982b. "Impacts of Deferred Pavement Maintenance" Proceedings, Second Transportation Research Workshop, Tempe, Ariz., Vol 2.

Markow, M. J., and Wong, T. K. F. 1983. "Life-Cycle Pavement Cost Allocation," Transportation Research Record 900, Transportation Research Board, Washington, D.C.

Marshall, K. T. 1986. "Some Inequalities in Queuing," Operations Research, Vol 16, pp 651-655.

Miller, Mark, and A. T. Kearney, Inc. 1981. "Review of National Defense, Emergency and Safety Issues Affecting the Waterways," National Waterways Study, Institute for Water Resources, US Army Corps of Engineers, Fort Belvoir, Va.

Mlakar, Paul F. 1984 (Dec). "A Statistical Study of the Condition of Civil Works Steel Structures," JAYCOR, Inc., J650-84-001/1303, CERL, Champaign, Ill.

Mlaker, Paul F. 1985 (Oct). Hazard Function for Miter Gates, Final Report J650-85- 005/1324, for Department of the Army, CERL, Champaign, Ill.

Moses, L. N., and Lowe, L. B. 1970 (Oct). Cost-Benefit Analysis for Inland Navigation Improvements, Vols 1-3, Institute of Water Resources, Fort Belvoir, VA.

National Waterways Study--A Framework for Decision Making, Final Report, January 1983.

Nelson, C. R. 1973. Applied Times Series Analysis for Management Forecasting, Holden-Day, Inc., Oakland, CA.

Scanlon, John M., Jr., et al. 1983 (Feb). "REMR Research Program Development Report," Final Report, Office of the Chief of Engineers, Washington, DC.

Shrestinian, David A. 1985 (Sep). "Preliminary Development of a Knowledge Based System for the Inspection and Maintenance of Lock Gates," Research Report R85-1', Massachusetts Institute of Technology, Cambridge, Mass.

Stanley Consultants. 1981, 1983.

Statistical Graphics Corporation. 1985. Statgraphics, Statistical Graphics System.

1985. Tow Cost Model User Manual. Huntington District Navigation Planning Support Control Center, USACE, Huntington, W. Va.

US Army Corps of Engineers. 1984 (Apr). Performance Monitoring System: Summary of Lock Statistics for April-June, 1983, Summary Report 84-SR-1, Washington, DC.

US Army Corps of Engineers. 1984 (May). Performance Monitoring System: Summary of Lock Statistics for January-March, 1983, Summary Report 84-SR-3, Washington, DC.

US Army Corps of Engineers. 1984 (Aug). Performance Monitoring System: Summary of Lock Statistics for October-December, 1983, Summary Report 84-SR-5, Washington, DC.

US Army Corps of Engineers. 1984 (Feb). Performance Monitoring System: Summary of Lock Statistics for July-September, 1984, Summary Report 84-SR-1, Washington, DC.

US Army Corps of Engineers. 1983. Digest of Water Resources Policies and Authorities, EP 1165-2-1, Washington, DC.

US Army Corps of Engineers. 1979. Waterway User Charges, prepared for AEI for Public Policy Research, Washington, DC.

US Congress. 1977 (Jul). "Financing Waterway Development; the User Charge Debate," CBO Staff Working Paper, Washington, DC.

US Department of Transportation. 1983 (Nov). Section 137 Studies, Climate and Apportionment and Interstate 4R Apportionment, submitted to the United States Congress.

Users' Manual: Inspection and Rating of Steel Sheet Pile Structures. 1986 (Dec). College of Engineering Report, Iowa State University, Submitted to the US Army Corps of Engineers, Contract No. DACA88-85-C-0007.

Water Resources Council (WRC). 1985. Manual of Procedures for Evaluation of National Economic Development (NED) Benefits and Costs in Water Resources Planning (Level C), US Army Corps of Engineers, Washington, DC.

Whitt, Ward. 1984. "Approximation for Departure Processes and Queues in Series," Naval Research Logistics Quarterly, Vol 31, pp 499-521.

Wilson, Moyt, G. 1978. "On the Application of Queuing Theory to Lock Capacity Analysis," Transportation Research, Vol 12, pp 175-180.

APPENDIX A: TIME SERIES ANALYSES OF LOCK REHABILITATION AND REPAIR EXPENDITURES

1. Box and Jenkins (1976)* time series models were applied to lock repair and rehabilitation data for Emsworth, Dashields, and Montgomery locks. The procedure is as follows (Nelson 1973), assuming Y is the variable to be forecast:

a. Y is transformed to a stationary variable so that the stochastic properties (mean, variance and covariance) are invariant with respect to time. Commonly first or second differences are used to transform the variable Y to Y*. A first difference is used to remove a general trend. Second differences stabilize the variance.

b. The Box-Jenkins model is

$$Y^*t = a_1 Y^*_{t-1} + a_2 Y^*_{t-2} + \dots + a_p Y_{t-p} + u_t$$
$$+ b_1 u_{t-1} + b_2 u_{t-2} + \dots + b_q u_{t-q}$$

where a and b are unknown parameters and the u are independent and identically distributed normal errors.

2. The model given above is an autoregressive integrated moving average model (ARIMA(p,d,q)) for Y where p is the number of lagged Y values representing the order of the autoregressive (AR) dimension of the model, d is the number of times Y is differenced to produce Y*, and q is the number of lagged values of the error term representing the order of the moving average (MA) dimension of the model. The three basic steps for obtaining an ARIMA model for forecasting are:

a. Identification - examination of the partial and autocorrelations to determine p, d and q.

b. Estimation - determination of a and b.

c. Diagnostic checking.

3. Graphical analysis of the series of expenditures for each lock over time indicated that maintenance expenditures are irregular. Figure 30 in Part III shows the maintenance expenditures as having a sawtoothed pattern with expenditures in 1 year commonly being followed by an absence of expenditures

---

* See References at the end of the main text.

in the next and vice versa. Thus, the expenditures demonstrate a policy that does not include annual regularly scheduled or preventative maintenance.

Identification

4. The graphs of the data, differenced time series data, and auto and partial correlations indicate that all three data sets exhibited similar data when second differences were taken.

5. The autocorrelations and partial correlations for the second differences are shown in Figures A1 to A6 for each lock. In all cases, the first autocorrelation and the first two partial correlations are significantly different from zero. The autocorrelations decay to zero exponentially in a sinusoidal pattern indicating a first order moving average. The partial autocorrelation decay to zero after the second lag, indicating a first order autoregressive process. Therefore, the model is identified as ARIMA (1,2,1) for all three locks. The model is given by the following:

$$Y^*_t = a_1 Y_{t-1} + u_t - b\, u_{t-1} + C \tag{A1}$$

where

$$Y^*_t = Y_{t+2} - Y_{t+1} - (Y_{t+1} - Y_t) = Y_{t+2} - 2Y_{t+1} + Y_t \tag{A2}$$

and

Y_t = the annual expenditure in 1977 dollars.

Estimation

6. The parameters a, b, and c were estimated using the program, Statgraphics (Statistical Graphics Corporation 1985) using a Marquardt nonlinear least squares algorithm. The results are given in Table A1.

Diagnostic Checking

7. The parameter estimates for a and b are of the same sign and order of magnitude for each lock indicating similar maintenance policies. To formally test the appropriateness of the model, the auto and partial

correlations of the residuals were plotted. In all cases these were not significantly different from zero. Furthermore, the chi-square test statistics (also given in Table A1) indicated that the probability of a larger value given white noise was greater than 60 percent in all cases. The t-stat for the parameter values also indicate that the coefficients are significantly different from zero. Finally, although not a good statistical test, alternative model specifications were either not appropriate or less statistically significant.

Limitations of the Model

8. Approximately 50 years of data were used to estimate the ARIMA model for each of the three locks. As noted by Lovesky (1986), major rehabilitations occur about every 20 years. Unfortunately, this cycle is too long compared with the length of the time series to be modeled. Therefore the model estimated is useful only for short-term forecasting, using the current maintenance strategies and technologies. In this application, the biggest limitation is the inability of the methodology to constrain the expenditures to be greater than zero. An alternative approach is to use log(Y+d) as the time series where d is small, but this failed to yield satisfactory models.

Forecasting

9. Forecasts using the model are based on Equation A1 and residuals as estimates for errors ut's. Where residuals are unknown they are assumed to be zero. Substituting Equation A2 into Equation A1 gives:

$$Y_{t+2} = 2Y_{t+1} + Y_t = aY_{t-1} + U_t + B\ U_{t-1} + C \qquad \text{(A3)}$$

therefore

$$Y_{t+2} = C + 2Y_{t+1} - Y_t + aY_{t-1} + b\ U_{t-1} + U_t \qquad \text{(A4)}$$

10. Substituting residuals for errors, Ut, Equation A3 can be used to forecast lock maintenance expenditures. For example, the data and residuals for Emsworth from 1975 to 1977 are given in Table A2.

11. These data are used to forecast expenditures for 1978 and 1979.

$$Y_{78} = 46,313 + 1.65Y_{77} - Y_{76} + 0.65\ U_{76} + U_{77} \quad \text{(A5)}$$

As Y_{1977} and C_{77} are unknown Y_{77} is used and C_{77} is assumed to be zero to forecast Y_{78}--a method known as bootstrapping.

then,

$$\begin{aligned} Y_{78} &= 46,313 + 1.65 * 192,088 - 180,685 + 0.65 * (-22,962 - 102,580) \quad \text{(A6)} \\ &= 65,068 \end{aligned}$$

That is, the method can be directly used to forecast future expenditures. However, the forecast expenditures beyond the existing data are likely to be unreliable.

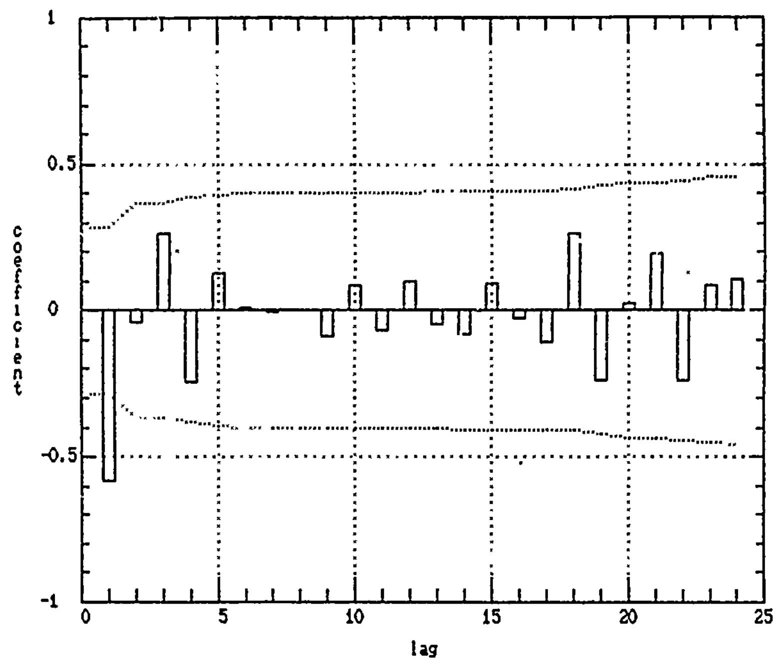


Figure A1. Estimated autocorrelations for second differences for Dashields project costs

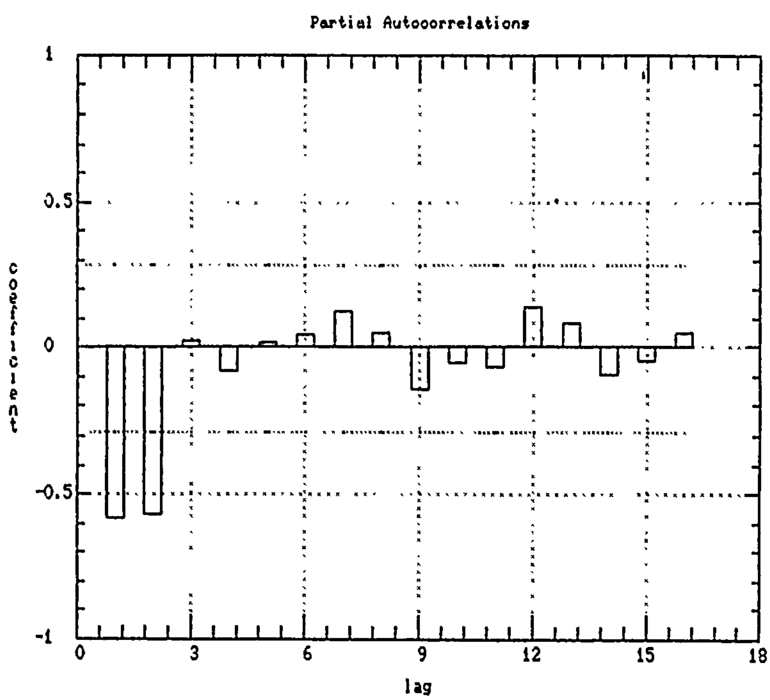


Figure A2. Estimated partial autocorrelations for second differences for Dashields project costs

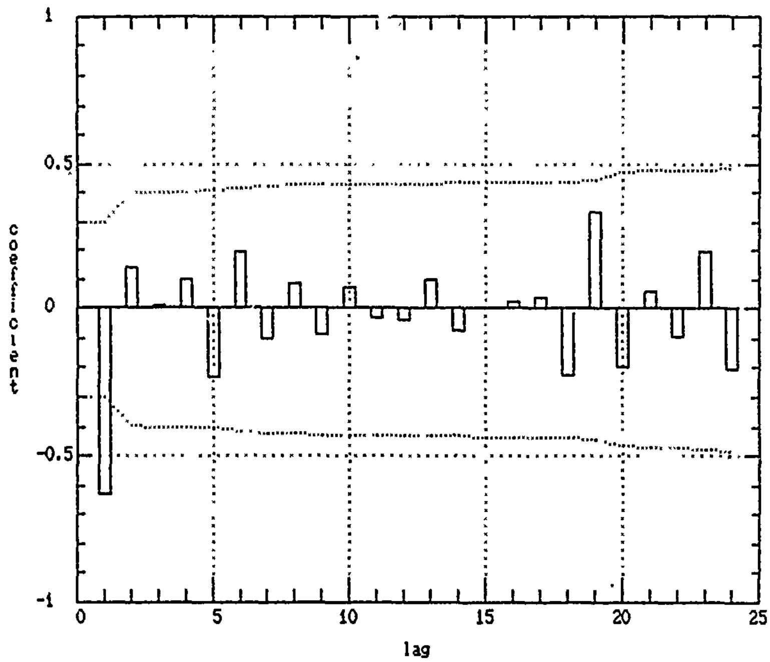


Figure A3. Estimated autocorrelations for second differences for Emsworth project costs

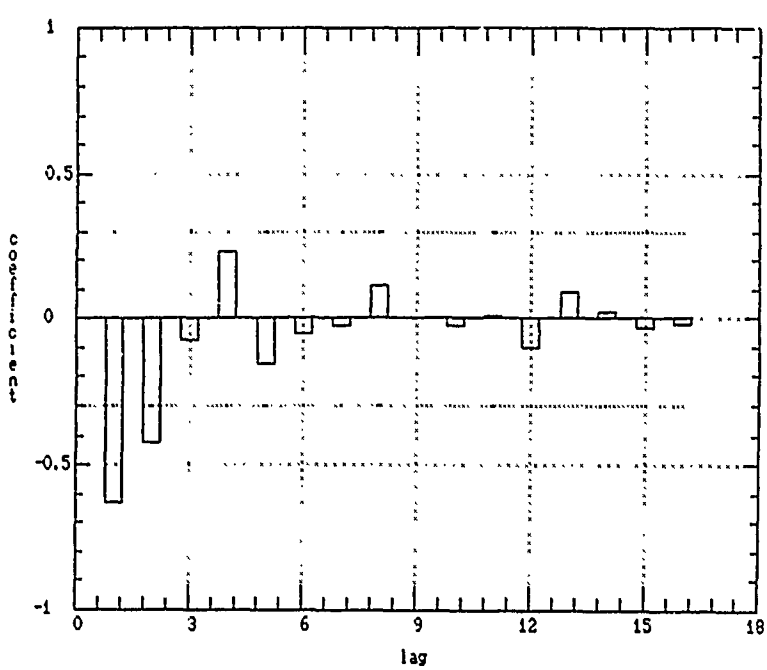


Figure A4. Estimated partial autocorrelations for second differences for Emsworth project costs

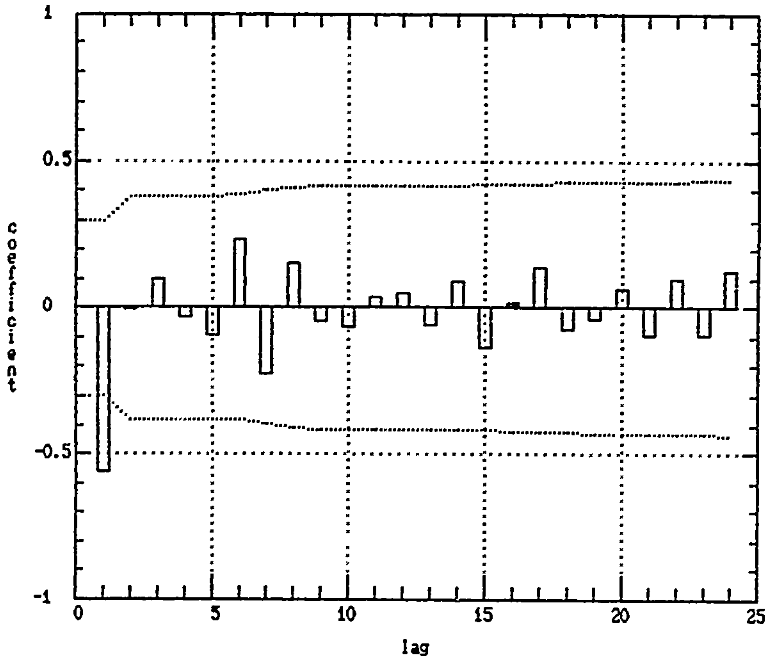


Figure A5. Estimated autocorrelations for second differences for Montgomery project costs

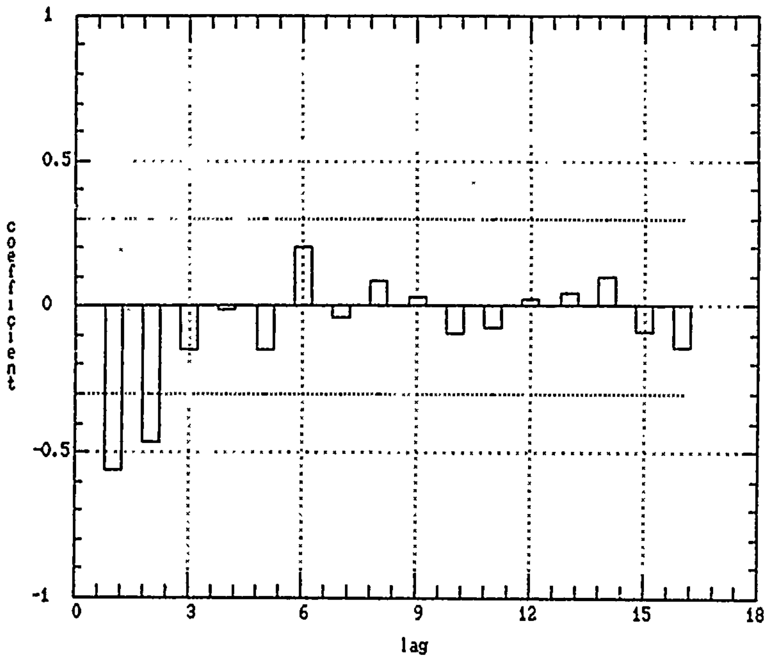


Figure A6. Estimated partial autocorrelations for second differences for Montgomery project costs

Table A1

Parameter Estimates

	Constant	Autoregressive	Moving Average	Chi-square
Dashields	-12,978	-0.36	0.88	15.35
Emsworth	46,315	-0.35	0.65	7.8
Montgomery	-9,190	0.31	1.04	9.68

Table A2

Maintenance Expenditures and Residuals for Emsworth

Year	Maintenance Expenditures	Residual
1975	156,489	82,422
1976	180,685	-22,962
1977	192,088	-102,580

APPENDIX B: STANLEY QUEUING SIMULATION MODEL CALCULATION OF REDUCTION IN LOCK WAITING TIMES AND ASSOCIATED BENEFITS

1. A queuing simulation model for the future Lock and Dam 26 (R) was developed by Stanley Consultants (1981, 1983)* of Muscatine, Iowa.

2. This model simulated a single-chambered lock and enabled the user to specify various operating rules, traffic volumes, process times, and stall durations. The primary purpose of this effort was to generate lock waiting time (e.g., lock delays) as a function of lock closure time.

3. In applying the model, it was decided to simulate operations in Lock and Dam 27, located some 10 miles downstream, using actual Performance Monitoring System (PMS) interarrival and process times obtained from detailed PMS data tape No. 17 for 1980. Figure B1(a) depicts Locks 26 and 27 as two service facilities in the simulated queuing system, with each facility servicing incoming barges. As the model simulates closure of Lock 26, incoming barges would accumulate and queue up upstream of Lock 26 increasing the time barges would have to wait before passing through the lock, as shown in Figure B1(b).

4. To determine the effects of a closure, hypothetical stalls of varying durations were introduced into the PMS data base no. 17 for random tow arrivals. The Stanley Consultants reasoned that in assigning the stall randomly by tow arrival sequence number, rather than by chronological arrival time, the likelihood of stall introduction would be proportional to traffic volume.

5. The development and use of a queuing model was felt justifiable, as no actual data (at the time) documented the aggregate waiting time for an unscheduled closure of a single-chamber lock in a high-traffic situation.

6. To enhance the statistical validity of these hypothetical closures, 10 stalls of identical duration were assigned to randomly arriving tows. The total resulting process time difference was then divided by 10 to determine the mean resulting increase in process time. Closures with durations of 1, 2,

---

* See References at the end of the main text.

6, 12, 24, 48, 96 and 240 hr were modeled for each of the randomly arriving tows.

7. Introduction of a 12-hr closure resulted in an addition of 388 hr to the mean process time. A 96-hr closure increased mean process time by 15,568 hr. Clearly, an exponential relationship is suggested by this distribution.

8. Regression of closure time against total waiting time was then performed using the Incentive Data Analysis (IDA) statistical package. Trials were made using logarithmic and exponential transformations of both variables. The following equation was selected for developing a closure time-waiting time table:

$$\ln T = 1.8039 + 1.7064 (\ln C) \tag{B1}$$

where ln = the symbol for natural log

T = total hours waiting time resulting from a closure

C = duration of closure in hours

9. The validity of this equation and simulation exercise becomes poor, however, after the closure duration exceeds 240 hr because:

- a. The confidence intervals widen exponentially as the independent variable increases.
- b. As the lock closure approaches 240 hr, shippers may begin to defer shipment or select alternative transport modes.
- c. The queuing model used for this analysis models only one lock. For accurate modeling of longer duration stalls, a system-wide model would be required.

10. It is appropriate to note that a 240-hr stall resulted in a simulated aggregate time for all vessels of 85,826 hr. If such a stall were introduced during the peak of the navigation season, it would require over a month for the queue to clear.

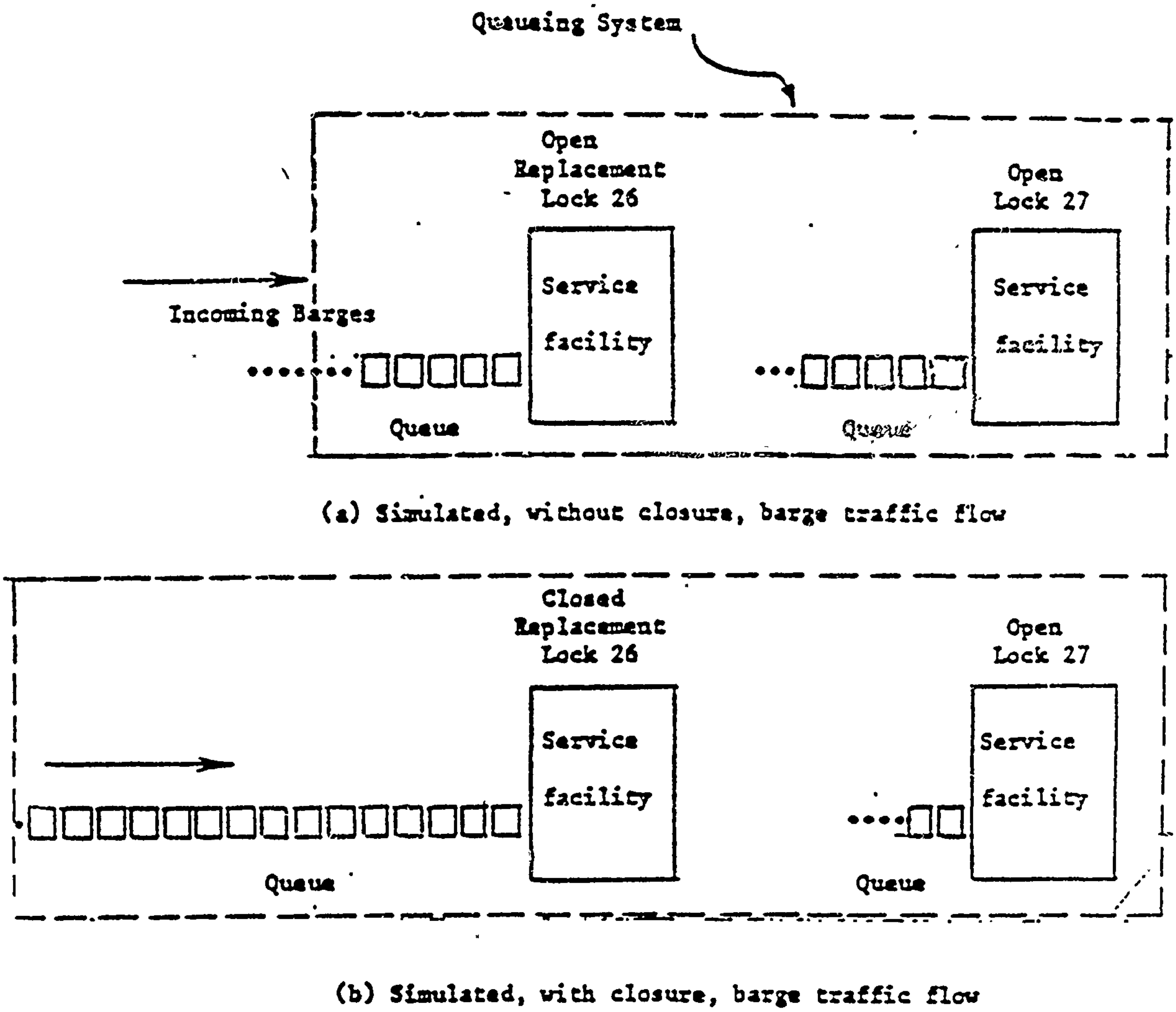
11. Waiting time costs were determined to be $6,900 per day (1982 price level) for the average 12,000-ton tow. These costs were developed by the US Army Engineer District, Saint Louis. A daily cost of $6,900 yielded an estimated hourly waiting cost of $287.50, which was applied to the closure time--total waiting time table to determine the cost incurred to tows during a stall. In the case of the hypothetical 200-hr stall, the total waiting time

cost incurred is in excess of $14 million, while a 24-hr stall would incur a $395,600 cost, as shown in Figure B2.

12. Perhaps more interesting are the marginal cost relationships. The difference in cost of a 24-hr closure and a 25-hr closure was determined to be approximately $28,500. The hourly cost differential between a 240-hr closure and a 241-hr closure was estimated at $143,500. This relationship occurs because as the closure duration increases, more tows enter the queue and begin to incur costs, even after the lock reopens. This rising marginal cost concept has definite implications on the importance of initiating repairs as soon as possible in the event of a major accident.

13. Figure B2 depicts the basic steps followed in the Stanley approach. Step 1: simulate lock performance as a queuing network to generate estimates of delay time T as a function of lock closure time C. Steps 2 and 3: apply regression analysis to the linear relationship ln T versus ln C (it may not be linear for other locks and dams). Step 4: apply transportation differential rates to the above to determine delay cost as a function of lock closure duration in hours.

14. This type of analysis is cited here because it can be a useful analytical tool for District personnel in determining navigation delay costs (e.g., navigation benefits if those delay costs are prevented by a proposed rehabilitation alternative).



(a) Simulated, without closure, barge traffic flow

(b) Simulated, with closure, barge traffic flow

Figure B1. Stanley queuing simulation model

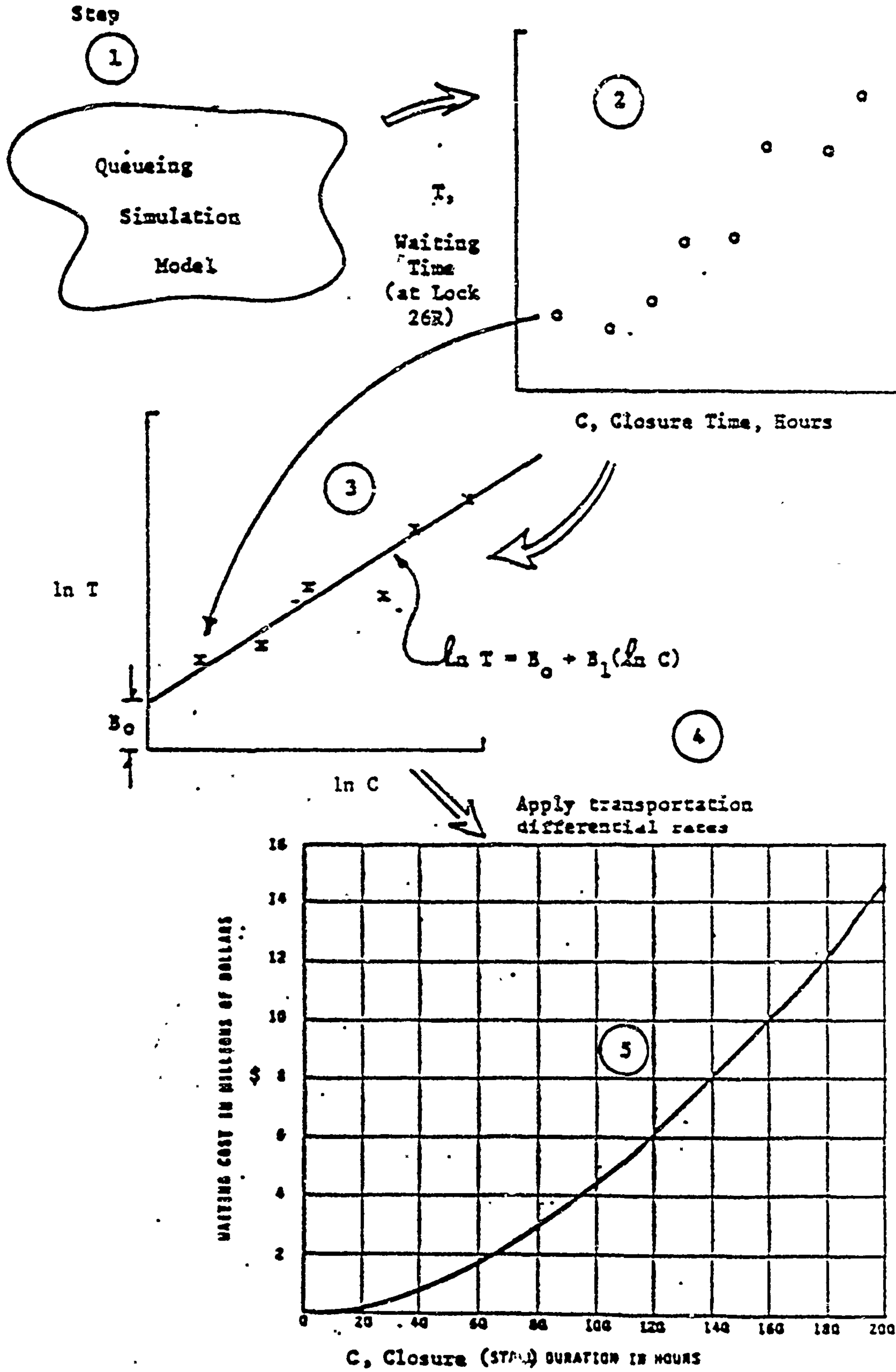


Figure B2. Determination of delay costs via queuing analysis

APPENDIX C: EXAMPLE INPUT DATA AND RESULTS OF PROTOTYPE REMR MANAGEMENT SYSTEM

```
name:                             P1
number:                           1
gate cond index std:              8.80
     time major:                  25.00
     time minor:                  10.00
     delta:                       0.45
     routine maint levels:
wall cond index std:              9.20
     time major:                  25.00
     time minor:                  10.00
     delta:                       0.20
     routine maint levels:
mech dev cond index std:          0.055
     time major:                  14.00
     time minor:                  7.00
     delta:                       0.024
     routine maint level:         8.00
```

```
ROUTINE MAINTAINENCE
Year 1986 Level 8.00
Year 0 Level 0.00
Year 0 Level 0.00
Year 0 Level 0.00
```

Figure C1. Windows describing REMR Policy 1

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
1986	8.00	9.70	0 12	8.00	9.70	0.10	9.95
1987	8.00	9.61	0.13	8.00	9.64	0.10	9.89
1988	8.00	9.55	0.13	8.00	9.61	0.11	9.86
1989	8.00	9.50	0.13	8.00	9.58	0.11	9.82
1990	8.00	9.44	0.13	8.00	9.55	0.11	9.78
1991	8.00	9.38	0.14	8.00	9.52	0.11	9.73
1992	8.00	9.32	0.14	8.00	9.49	0.12	9.95
1993	8.00	9.26	0.14	8.00	9.46	0.12	9.89
1994	8.00	9.19	0.15	8.00	9.43	0.12	9.86
1995	8.00	9.64	0.11	8.00	9.63	0.09	9.82

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
1996	8.00	9.55	0.11	8.00	9.61	0.09	9.78
1997	8.00	9.50	0.12	8.00	9.58	0.10	9.73
1998	8.00	9.44	0.12	8.00	9.55	0.10	9.69
1999	8.00	9.38	0.12	8.00	9.52	0.10	9.95
2000	8.00	9.32	0.12	8.00	9.49	0.10	9.89
2001	8.00	9.26	0.13	8.00	9.46	0.11	9.86
2002	8.00	9.19	0.13	8.00	9.43	0.11	9.82
2003	8.00	9.12	0.13	8.00	9.40	0.11	9.78
2004	8.00	9.04	0.14	8.00	9.37	0.11	9.73
2005	8.00	9.49	0.10	8.00	9.57	0.08	9.69

----- PRESS A KEY FOR MORE -----

Figure C2. Facility Condition Report for REMR Policy 1 (Continued)

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
2006	8.00	9.44	0.10	8.00	9.55	0.09	9.93
2007	8.00	9.38	0.11	8.00	9.52	0.09	9.89
2008	8.00	9.32	0.11	8.00	9.49	0.09	9.86
2009	8.00	9.26	0.11	8.00	9.46	0.09	9.82
2010	8.00	9.80	0.12	8.00	9.80	0.10	9.78
2011	8.00	9.61	0.12	8.00	9.64	0.10	9.73
2012	8.00	9.55	0.13	8.00	9.61	0.10	9.69
2013	8.00	9.50	0.13	8.00	9.58	0.11	9.95
2014	8.00	9.44	0.13	8.00	9.55	0.11	9.89
2015	8.00	9.38	0.13	8.00	9.52	0.11	9.86

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
2016	8.00	9.32	0.14	8.00	9.49	0.11	9.82
2017	8.00	9.26	0.14	8.00	9.46	0.12	9.78
2018	8.00	9.19	0.14	8.00	9.43	0.12	9.73
2019	8.00	9.12	0.15	8.00	9.40	0.12	9.69
2020	8.00	9.57	0.11	8.00	9.60	0.09	9.93
2021	8.00	9.50	0.11	8.00	9.58	0.09	9.89
2022	8.00	9.44	0.12	8.00	9.55	0.10	9.86
2023	8.00	9.38	0.12	8.00	9.52	0.10	9.82
2024	8.00	9.32	0.12	8.00	9.49	0.10	9.78
2025	8.00	9.26	0.12	8.00	9.46	0.10	9.73

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
2026	8.00	9.19	0.13	8.00	9.43	0.11	9.69
2027	8.00	9.12	0.13	8.00	9.40	0.11	9.95
2028	8.00	9.04	0.13	8.00	9.37	0.11	9.89
2029	8.00	8.96	0.14	8.00	9.34	0.11	9.86
2030	8.00	9.41	0.10	8.00	9.54	0.08	9.82
2031	8.00	9.38	0.10	8.00	9.52	0.09	9.78
2032	8.00	9.32	0.11	8.00	9.49	0.09	9.73
2033	8.00	9.26	0.11	8.00	9.46	0.09	9.69
2034	8.00	9.19	0.11	8.00	9.43	0.09	9.93
2035	8.00	9.80	0.12	8.00	9.80	0.10	9.89
AVE.	8.00	9.37	0.12	8.00	9.52	0.10	9.82

----- PRESS A KEY FOR MORE -----

Figure C2. (Concluded)

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
1986	4249.37	1.95	0.17	0.00	0.62
1987	4453.53	1.94	0.24	0.00	0.65
1988	4620.68	1.94	0.28	0.00	0.67
1989	4757.54	1.94	0.31	0.00	0.68
1990	4869.59	1.94	0.34	0.00	0.70
1991	4961.32	1.93	0.38	0.00	0.72
1992	5036.43	1.94	0.18	5.00	0.65
1993	5097.92	1.93	0.25	0.00	0.67
1994	5148.27	1.93	0.28	0.00	0.69
1995	5189.49	1.94	0.31	5.00	0.70

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
1996	5223.24	1.94	0.34	0.00	0.71
1997	5250.87	1.94	0.37	0.00	0.73
1998	5273.49	1.93	0.40	0.00	0.75
1999	5292.01	1.94	0.17	40.00	0.65
2000	5307.18	1.94	0.24	0.00	0.68
2001	5319.59	1.93	0.28	0.00	0.69
2002	5329.75	1.93	0.31	0.00	0.71
2003	5338.08	1.93	0.34	0.00	0.73
2004	5344.89	1.92	0.37	0.00	0.74
2005	5350.47	1.93	0.40	5.00	0.75

----- PRESS A KEY FOR MORE -----

Figure C3. Facility Service Report for REMR Policy 1 (Continued)

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2006	5355.04	1.94	0.20	5.00	0.66
2007	5358.78	1.94	0.24	0.00	0.68
2008	5361.84	1.93	0.28	0.00	0.69
2009	5364.34	1.93	0.31	0.00	0.71
2010	5366.40	1.94	0.34	40.00	0.72
2011	5368.08	1.94	0.37	0.00	0.74
2012	5369.45	1.94	0.40	0.00	0.76
2013	5370.[illegible]8	1.94	0.18	40.00	0.66
2014	5371.50	1.94	0.24	0.00	0.68
2015	5372.26	1.94	0.28	0.00	0.69

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2016	5372.87	1.93	0.31	0.00	0.71
2017	5373.38	1.93	0.35	0.00	0.73
2018	5373.79	1.93	0.38	0.00	0.74
2019	5374.13	1.92	0.41	0.00	0.76
2020	5374.41	1.94	0.20	5.00	0.66
2021	5374.64	1.94	0.24	0.00	0.68
2022	5374.82	1.94	0.28	0.00	0.69
2023	5374.98	1.94	0.31	0.00	0.71
2024	5375.10	1.93	0.34	0.00	0.72
2025	5375.20	1.93	0.37	0.00	0.74

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2026	5375.29	1.93	0.40	0.00	0.76
2027	5375.36	1.93	0.18	40.00	0.66
2028	5375.41	1.93	0.24	0.00	0.68
2029	5375.46	1.92	0.28	0.00	0.70
2030	5375.50	1.94	0.31	5.00	0.71
2031	5375.53	1.93	0.34	0.00	0.72
2032	5375.55	1.93	0.37	0.00	0.74
2033	5375.57	1.93	0.40	0.00	0.76
2034	5375.59	1.93	0.20	5.00	0.67
2035	5375.60	1.95	0.24	40.00	0.67
AVE.	5251.40	1.93	0.30	6.80	0.70

Total expected but unscheduled down time is 0.73 days

----- PRESS A KEY FOR MORE -----

Figure C3. (Concluded)

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	gate rep	wall rep	mech rep	routine rep	damage	total
1986	0	0	0	81	15	96
1987	0	0	1	81	15	97
1988	0	0	1	81	15	97
1989	0	0	1	81	15	97
1990	0	0	1	81	15	97
1991	0	0	1	81	15	97
1992	0	0	135	81	15	231
1993	0	0	0	81	15	96
1994	0	0	1	81	15	97
1995	780	454	1	81	15	1331

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
1996	0	0	1	81	15	97
1997	0	0	1	81	15	97
1998	0	0	1	81	15	97
1999	0	0	200	81	15	296
2000	0	0	0	81	15	96
2001	0	0	1	81	15	97
2002	0	0	1	81	15	97
2003	0	0	1	81	15	97
2004	0	0	1	81	15	97
2005	780	454	1	81	15	1331

----- PRESS A KEY FOR MORE -----

Figure C4. Facility Cost Report for REMR Policy 1 (Continued)

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2006	0	0	147	81	15	243
2007	0	0	0	81	15	96
2008	0	0	1	81	15	97
2009	0	0	1	81	15	97
2010	1463	1572	1	81	15	3132
2011	0	0	1	81	15	97
2012	0	0	1	81	15	97
2013	0	0	200	81	15	296
2014	0	0	0	81	15	96
2015	0	0	1	81	15	97

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2016	0	0	1	81	15	97
2017	0	0	1	81	15	97
2018	0	0	1	81	15	97
2019	0	0	1	81	15	97
2020	780	454	147	81	15	1477
2021	0	0	0	81	15	96
2022	0	0	1	81	15	97
2023	0	0	1	81	15	97
2024	0	0	1	81	15	97
2025	0	0	1	81	15	97

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2026	0	0	1	81	15	97
2027	0	0	200	81	15	296
2028	0	0	0	81	15	96
2029	0	0	1	81	15	97
2030	780	454	1	81	15	1331
2031	0	0	1	81	15	97
2032	0	0	1	81	15	97
2033	0	0	1	81	15	97
2034	0	0	147	81	15	243
2035	1524	1616	0	81	15	3236
EUC.	65	47	18	78	15	222
TOT.	783	563	212	939	178	2675

Discount rate - 8.125%   Costs are in thousands of dollars

----- PRESS A KEY FOR MORE -----

Figure C4. (Concluded)

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	agency cost	user cost	total cost
1986	96	265	361
1987	97	289	386
1988	97	309	406
1989	97	327	424
1990	97	344	441
1991	97	361	458
1992	231	345	576
1993	96	344	440
1994	97	356	453
1995	1331	381	1712

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
1996	97	375	472
1997	97	386	483
1998	97	398	495
1999	296	1508	1804
2000	96	361	457
2001	97	370	467
2002	97	379	476
2003	97	389	486
2004	97	399	496
2005	1331	423	1754

----- PRESS A KEY FOR MORE -----

Figure C5. Facility Total Cost Report for REMR Policy 1 (Continued)

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2006	243	376	619
2007	96	364	460
2008	97	373	470
2009	97	381	478
2010	3132	1563	4695
2011	97	397	494
2012	97	407	504
2013	296	1531	1827
2014	96	366	462
2015	97	374	471

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2016	97	383	480
2017	97	392	489
2018	97	401	498
2019	97	411	508
2020	1477	377	1854
2021	96	365	461
2022	97	374	471
2023	97	382	479
2024	97	391	4[illegible]
2025	97	400	497

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2026	97	410	507
2027	296	1535	1831
2028	96	369	465
2029	97	378	475
2030	1331	400	1731
2031	97	390	487
2032	97	399	496
2033	97	409	506
2034	243	379	622
2035	3236	1542	4778
EUC.	222	395	617
TOT.	2675	4761	7436

Discount rate = 8.125%   Costs are in thousands of dollars

----- PRESS A KEY FOR MORE -----

Figure C5. (Concluded)

```
name:                          P1
number:                        2
gate cond index std:           7.60
     time major:               30.00
     time minor:               15.00
     delta:                    0.45
     routine maint levels:
wall cond index std:           8.90
     time major:               30.00
     time minor:               15.00
     delta:                    0.20
     routine maint levels:
mech dev cond index std:       0.064
     time major:               15.00
     time minor:               8.00
     delta:                    0.024
     routine maint level:      7.00
```

```
ROUTINE MAINTAINENCE
Year 1986 Level 7.00
Year 0 Level 0.00
Year 0 Level 0.00
Year 0 Level 0.00
```

Figure C6. Windows describing REMR Policy 2

MANAGEMENT SYSTEM FOR CIVIL WORKS   PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
1986	7.00	9.70	0.12	7.00	9.70	0.10	9.95
1987	7.00	9.61	0.13	7.00	9.64	0.11	9.89
1988	7.00	9.55	0.13	7.00	9.61	0.11	9.85
1989	7.00	9.50	0.13	7.00	9.58	0.11	9.81
1990	7.00	9.44	0.14	7.00	9.55	0.11	9.77
1991	7.00	9.38	0.14	7.00	9.52	0.12	9.72
1992	7.00	9.32	0.14	7.00	9.49	0.12	9.68
1993	7.00	9.26	0.15	7.00	9.46	0.12	9.92
1994	7.00	9.19	0.15	7.00	9.43	0.13	9.89
1995	7.00	9.12	0.16	7.00	9.40	0.13	9.85

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
1996	7.00	9.04	0.16	7.00	9.37	0.13	9.81
1997	7.00	8.96	0.17	7.00	9.34	0.14	9.77
1998	7.00	8.88	0.17	7.00	9.31	0.14	9.72
1999	7.00	8.80	0.17	7.00	9.27	0.15	9.68
2000	7.00	9.25	0.13	7.00	9.47	0.11	9.95
2001	7.00	9.19	0.13	7.00	9.43	0.11	9.89
2002	7.00	9.12	0.14	7.00	9.40	0.12	9.85
2003	7.00	9.04	0.14	7.00	9.37	0.12	9.81
2004	7.00	8.96	0.15	7.00	9.34	0.12	9.77
2005	7.00	8.88	0.15	7.00	9.31	0.12	9.72

----- PRESS A KEY FOR MORE -----

Figure C7. Facility Condition Report for REMR Policy 2 (Continued)

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
2006	7.00	8.80	0.15	7.00	9.27	0.13	9.68
2007	7.00	8.70	0.16	7.00	9.24	0.13	9.62
2008	7.00	8.61	0.16	7.00	9.21	0.14	9.86
2009	7.00	8.51	0.17	7.00	9.17	0.14	9.81
2010	7.00	8.40	0.17	7.00	9.13	0.14	9.77
2011	7.00	8.29	0.18	7.00	9.10	0.15	9.72
2012	7.00	8.17	0.18	7.00	9.06	0.15	9.68
2013	7.00	8.05	0.19	7.00	9.02	0.15	9.62
2014	7.00	7.92	0.19	7.00	8.98	0.16	9.57
2015	7.00	9.80	0.12	7.00	9.80	0.10	9.95

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
2016	7.00	9.61	0.12	7.00	9.64	0.10	9.89
2017	7.00	9.55	0.13	7.00	9.61	0.11	9.85
2018	7.00	9.50	0.13	7.00	9.58	0.11	9.81
2019	7.00	9.44	0.13	7.00	9.55	0.11	9.77
2020	7.00	9.38	0.14	7.00	9.52	0.11	9.72
2021	7.00	9.32	0.14	7.00	9.49	0.12	9.68
2022	7.00	9.26	0.14	7.00	9.46	0.12	9.62
2023	7.00	9.19	0.15	7.00	9.43	0.12	9.86
2024	7.00	9.12	0.15	7.00	9.40	0.13	9.81
2025	7.00	9.04	0.16	7.00	9.37	0.13	9.77

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
2026	7.00	8.96	0.16	7.00	9.34	0.13	9.72
2027	7.00	8.88	0.17	7.00	9.31	0.14	9.68
2028	7.00	8.80	0.17	7.00	9.27	0.14	9.62
2029	7.00	8.70	0.17	7.00	9.24	0.15	9.57
2030	7.00	9.15	0.13	7.00	9.44	0.11	9.95
2031	7.00	9.04	0.13	7.00	9.40	0.11	9.89
2032	7.00	8.96	0.14	7.00	9.37	0.12	9.85
2033	7.00	8.88	0.14	7.00	9.34	0.12	9.81
2034	7.00	8.80	0.15	7.00	9.31	0.12	9.77
2035	7.00	8.70	0.15	7.00	9.27	0.12	9.72
AVE.	7.00	9.03	0.15	7.00	9.39	0.12	9.78

----- PRESS A KEY FOR MORE -----

Figure C7. (Concluded)

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
1986	4249.37	1.95	0.17	0.00	0.62
1987	4453.53	1.94	0.24	0.00	0.65
1988	4620.68	1.94	0.28	0.00	0.67
1989	4757.54	1.94	0.32	0.00	0.69
1990	4869.59	1.94	0.35	0.00	0.71
1991	4961.32	1.93	0.38	0.00	0.73
1992	5036.43	1.93	0.41	0.00	0.75
1993	5097.92	1.93	0.22	5.00	0.66
1994	5148.27	1.93	0.25	0.00	0.68
1995	5189.49	1.93	0.29	0.00	0.69

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
1996	5223.24	1.93	0.32	0.00	0.71
1997	5250.87	1.92	0.35	0.00	0.73
1998	5273.49	1.92	0.39	0.00	0.75
1999	5292.01	1.91	0.42	0.00	0.77
2000	5307.18	1.93	0.18	40.00	0.66
2001	5319.59	1.93	0.25	0.00	0.68
2002	5329.75	1.93	0.28	0.00	0.70
2003	5338.08	1.93	0.32	0.00	0.71
2004	5344.89	1.92	0.35	0.00	0.73
2005	5350.47	1.92	0.38	0.00	0.75

----- PRESS A KEY FOR MORE -----

Figure C8. Facility Service Report for REMR Policy 2 (Continued)

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2006	5355.04	1.91	0.41	0.00	0.77
2007	5358.78	1.91	0.44	0.00	0.79
2008	5361.84	1.91	0.28	5.00	0.70
2009	5364.34	1.90	0.32	0.00	0.73
2010	5366.40	1.90	0.35	0.00	0.75
2011	5368.08	1.89	0.39	0.00	0.77
2012	5369.45	1.88	0.42	0.00	0.79
2013	5370.58	1.87	0.45	0.00	0.81
2014	5371.50	1.86	0.48	0.00	0.84
2015	5372.26	1.95	0.17	40.00	0.65

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2016	5372.87	1.94	0.24	0.00	0.68
2017	5373.38	1.94	0.28	0.00	0.69
2018	5373.79	1.94	0.32	0.00	0.71
2019	5374.13	1.94	0.35	0.00	0.73
2020	5374.41	1.93	0.38	0.00	0.74
2021	5374.64	1.93	0.41	0.00	0.76
2022	5374.82	1.93	0.44	0.00	0.78
2023	5374.98	1.93	0.28	5.00	0.69
2024	5375.10	1.93	0.32	0.00	0.71
2025	5375.20	1.92	0.35	0.00	0.73

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2026	5375.29	1.92	0.38	0.00	0.75
2027	5375.36	1.92	0.41	0.00	0.77
2028	5375.41	1.91	0.45	0.00	0.79
2029	5375.46	1.91	0.48	0.00	0.82
2030	5375.50	1.93	0.18	40.00	0.66
2031	5375.53	1.93	0.25	0.00	0.68
2032	5375.55	1.92	0.28	0.00	0.70
2033	5375.57	1.92	0.32	0.00	0.72
2034	5375.59	1.92	0.35	0.00	0.74
2035	5375.60	1.91	0.38	0.00	0.75
AVE.	5251.40	1.92	0.33	4.70	0.72

Total expected but unscheduled down time is 0.84 days

----- PRESS A KEY FOR MORE -----

Figure C8. (Concluded)

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	gate rep	wall rep	mech rep	routine rep	damage	total
1986	0	0	0	62	15	78
1987	0	0	1	62	15	79
1988	0	0	1	62	15	78
1989	0	0	1	62	15	78
1990	0	0	1	62	15	78
1991	0	0	1	62	15	78
1992	0	0	1	62	15	78
1993	0	0	147	62	15	225
1994	0	0	0	62	15	78
1995	0	0	1	62	15	78

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
1996	0	0	1	62	15	78
1997	0	0	1	62	15	78
1998	0	0	1	62	15	78
1999	0	0	1	62	15	78
2000	780	454	203	62	15	1514
2001	0	0	0	62	15	78
2002	0	0	1	62	15	78
2003	0	0	1	62	15	78
2004	0	0	1	62	15	78
2005	0	0	1	62	15	78

----- PRESS A KEY FOR MORE -----

Figure C9. Facility Cost Report for REMR Policy 2 (Continued)

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2006	0	0	1	62	15	78
2007	0	0	1	62	15	78
2008	0	0	147	62	15	225
2009	0	0	0	62	15	78
2010	0	0	1	62	15	78
2011	0	0	1	62	15	78
2012	0	0	1	62	15	78
2013	0	0	1	62	15	78
2014	0	0	1	62	15	79
2015	2678	2291	230	62	15	5276

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2016	0	0	0	62	15	78
2017	0	0	1	62	15	78
2018	0	0	1	62	15	78
2019	0	0	1	62	15	78
2020	0	0	1	62	15	78
2021	0	0	1	62	15	78
2022	0	0	1	62	15	78
2023	0	0	147	62	15	225
2024	0	0	0	62	15	78
2025	0	0	1	62	15	78

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2026	0	0	1	62	15	78
2027	0	0	1	62	15	78
2028	0	0	1	62	15	78
2029	0	0	1	62	15	79
2030	780	454	230	62	15	1541
2031	0	0	0	62	15	78
2032	0	0	1	62	15	78
2033	0	0	1	62	15	78
2034	0	0	1	62	15	78
2035	0	0	1	62	15	78
EUC.	40	29	17	60	15	160
TOT.	485	346	199	723	178	1931

Discount rate = 8.125%   Costs are in thousands of dollars

----- PRESS A KEY FOR MORE -----

Figure C9. (Concluded)

MANAGEMENT SYSTEM FOR CIVIL WORKS   PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	agency cost	user cost	total cost
1986	78	265	343
1987	79	289	368
1988	78	309	387
1989	78	328	406
1990	78	345	423
1991	78	362	440
1992	78	379	457
1993	225	358	583
1994	78	349	427
1995	78	361	439

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
1996	78	373	451
1997	78	384	462
1998	78	396	474
1999	78	409	487
2000	1514	1514	3028
2001	78	363	441
2002	78	373	451
2003	78	382	460
2004	78	392	470
2005	78	403	481

----- PRESS A KEY FOR MORE -----

Figure C10. Facility Total Cost Report for REMR Policy 2 (Continued)

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2006	78	414	492
2007	78	426	504
2008	225	397	622
2009	78	391	469
2010	78	402	480
2011	78	413	491
2012	78	425	503
2013	78	438	516
2014	79	453	532
2015	5276	1530	6806

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2016	78	365	443
2017	78	374	452
2018	78	382	460
2019	78	391	469
2020	78	401	479
2021	78	412	490
2022	78	423	501
2023	225	393	618
2024	78	386	464
2025	78	395	473

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2026	78	405	483
2027	78	416	494
2028	78	428	506
2029	79	441	520
2030	1541	1535	3076
2031	78	369	447
2032	78	378	456
2033	78	387	465
2034	78	397	475
2035	78	407	485
EUC.	160	381	542
TOT.	1931	4601	6531

Discount rate = 8.125%   Costs are in thousands of dollars

----- PRESS A KEY FOR MORE -----

Figure C10. (Concluded)

```
name:                           P1
number:                         3
gate cond index std:            6.70
     time major:                35.00
     time minor:                20.00
     delta:                     0.45
     routine maint levels:
wall cond index std:            8.70
     time major:                35.00
     time minor:                20.00
     delta:                     0.20
     routine maint levels:
mech dev cond index std:        0.084
     time major:                16.00
     time minor:                9.00
     delta:                     0.024
     routine maint level:       6.00
```

```
ROUTINE MAINTAINENCE
Year 1986 Level.6.00
Year 0 Level 0.00
Year 0 Level 0.00
Year 0 Level 0.00
```

Figure C11. Windows describing REMR Policy 3

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
1986	6.00	9.70	0.12	6.00	9.70	0.10	9.95
1987	6.00	9.61	0.13	6.00	9.64	0.11	9.89
1988	6.00	9.55	0.13	6.00	9.61	0.11	9.85
1989	6.00	9.50	0.14	6.00	9.58	0.11	9.81
1990	6.00	9.44	0.14	6.00	9.55	0.12	9.76
1991	6.00	9.38	0.15	6.00	9.52	0.12	9.72
1992	6.00	9.32	0.15	6.00	9.49	0.13	9.67
1993	6.00	9.26	0.16	6.00	9.46	0.13	9.61
1994	6.00	9.19	0.16	6.00	9.43	0.13	9.85
1995	6.00	9.12	0.17	6.00	9.40	0.14	9.81

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
1996	6.00	9.04	0.17	6.00	9.37	0.14	9.76
1997	6.00	8.96	0.18	6.00	9.34	0.15	9.72
1998	6.00	8.88	0.18	6.00	9.31	0.15	9.67
1999	6.00	8.80	0.19	6.00	9.27	0.16	9.61
2000	6.00	8.70	0.19	6.00	9.24	0.16	9.55
2001	6.00	8.61	0.20	6.00	9.21	0.17	9.95
2002	6.00	8.51	0.21	6.00	9.17	0.17	9.89
2003	6.00	8.40	0.21	6.00	9.13	0.18	9.85
2004	6.00	8.29	0.22	6.00	9.10	0.18	9.81
2005	6.00	8.74	0.17	6.00	9.30	0.14	9.76

----- PRESS A KEY FOR MORE -----

Figure C12. Facility Condition Report for REMR Policy 3 (Continued)

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
2006	6.00	8.61	0.17	6.00	9.27	0.14	9.72
2007	6.00	8.51	0.18	6.00	9.24	0.15	9.67
2008	6.00	8.40	0.18	6.00	9.21	0.15	9.61
2009	6.00	8.29	0.19	6.00	9.17	0.16	9.55
2010	6.00	8.17	0.20	6.00	9.13	0.16	9.79
2011	6.00	8.05	0.20	6.00	9.10	0.17	9.76
2012	6.00	7.92	0.21	6.00	9.06	0.17	9.72
2013	6.00	7.79	0.22	6.00	9.02	0.18	9.67
2014	6.00	7.65	0.22	6.00	8.98	0.19	9.61
2015	6.00	7.50	0.23	6.00	8.93	0.19	9.55

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
2016	6.00	7.35	0.24	6.00	8.89	0.20	9.49
2017	6.00	7.19	0.24	6.00	8.85	0.20	9.95
2018	6.00	7.02	0.25	6.00	8.80	0.21	9.89
2019	6.00	6.84	0.26	6.00	8.76	0.22	9.85
2020	6.00	9.80	0.12	6.00	9.80	0.10	9.81
2021	6.00	9.61	0.12	6.00	9.64	0.10	9.76
2022	6.00	9.55	0.13	6.00	9.61	0.11	9.72
2023	6.00	9.50	0.13	6.00	9.58	0.11	9.67
2024	6.00	9.44	0.14	6.00	9.55	0.11	9.61
2025	6.00	9.38	0.14	6.00	9.52	0.12	9.55

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
2026	6.00	9.32	0.15	6.00	9.49	0.12	9.79
2027	6.00	9.26	0.15	6.00	9.46	0.13	9.76
2028	6.00	9.19	0.16	6.00	9.43	0.13	9.72
2029	6.00	9.12	0.16	6.00	9.40	0.13	9.67
2030	6.00	9.04	0.17	6.00	9.37	0.14	9.61
2031	6.00	8.96	0.17	6.00	9.34	0.14	9.55
2032	6.00	8.88	0.18	6.00	9.31	0.15	9.49
2033	6.00	8.80	0.18	6.00	9.27	0.15	9.95
2034	6.00	8.70	0.19	6.00	9.24	0.16	9.89
2035	6.00	8.61	0.19	6.00	9.21	0.16	9.85
AVE.	6.00	8.75	0.18	6.00	9.31	0.15	9.73

----- PRESS A KEY FOR MORE -----

Figure C12. (Concluded)

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
1986	4249.37	1.95	0.18	0.00	0.62
1987	4453.53	1.94	0.25	0.00	0.65
1988	4620.68	1.94	0.29	0.00	0.67
1989	4757.54	1.94	0.32	0.00	0.69
1990	4869.59	1.94	0.35	0.00	0.71
1991	4961.32	1.93	0.39	0.00	0.73
1992	5036.43	1.93	0.42	0.00	0.75
1993	5097.92	1.93	0.45	0.00	0.78
1994	5148.27	1.93	0.29	5.00	0.69
1995	5189.49	1.93	0.33	0.00	0.71

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
1996	5223.24	1.92	0.36	0.00	0.73
1997	5250.87	1.92	0.39	0.00	0.75
1998	5273.49	1.92	0.42	0.00	0.77
1999	5292.01	1.91	0.46	0.00	0.80
2000	5307.18	1.91	0.49	0.00	0.82
2001	5319.59	1.91	0.20	40.00	0.67
2002	5329.75	1.91	0.27	0.00	0.70
2003	5338.08	1.90	0.30	0.00	0.72
2004	5344.89	1.89	0.34	0.00	0.74
2005	5350.47	1.91	0.36	5.00	0.74

----- PRESS A KEY FOR MORE -----

Figure C13. Facility Service Report for REMR Policy 3 (Continued)

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2006	5355.04	1.91	0.39	0.00	0.76
2007	5358.78	1.90	0.42	0.00	0.78
2008	5361.84	1.90	0.46	0.00	0.81
2009	5364.34	1.89	0.49	0.00	0.83
2010	5366.40	1.89	0.34	5.00	0.75
2011	5368.08	1.88	0.36	0.00	0.76
2012	5369.45	1.87	0.40	0.00	0.78
2013	5370.58	1.86	0.43	0.00	0.81
2014	5371.50	1.84	0.46	0.00	0.84
2015	5372.26	1.82	0.49	0.00	0.87

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2016	5372.87	1.81	0.53	0.00	0.91
2017	5373.38	1.80	0.22	40.00	0.74
2018	5373.79	1.77	0.28	0.00	0.77
2019	5374.13	1.74	0.32	0.00	0.81
2020	5374.41	1.94	0.32	40.00	0.71
2021	5374.64	1.94	0.35	0.00	0.73
2022	5374.82	1.94	0.38	0.00	0.74
2023	5374.98	1.93	0.42	0.00	0.76
2024	5375.10	1.93	0.45	0.00	0.79
2025	5375.20	1.93	0.48	0.00	0.81

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2026	5375.29	1.93	0.33	5.00	0.72
2027	5375.36	1.93	0.36	0.00	0.73
2028	5375.41	1.93	0.39	0.00	0.75
2029	5375.46	1.92	0.42	0.00	0.77
2030	5375.50	1.92	0.45	0.00	0.79
2031	5375.53	1.92	0.48	0.00	0.82
2032	5375.55	1.91	0.52	0.00	0.84
2033	5375.57	1.92	0.19	40.00	0.67
2034	5375.59	1.91	0.26	0.00	0.69
2035	5375.60	1.91	0.30	0.00	0.71
AVE.	5251.40	1.90	0.37	4.50	0.75

Total expected but unscheduled down time is 0.94 days

----- PRESS A KEY FOR MORE -----

Figure C13. (Concluded)

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	gate rep	wall rep	mech rep	routine rep	damage	total
1986	0	0	0	46	15	61
1987	0	0	1	46	15	62
1988	0	0	1	46	15	62
1989	0	0	1	46	15	62
1990	0	0	1	46	15	62
1991	0	0	1	46	15	62
1992	0	0	1	46	15	62
1993	0	0	1	46	15	62
1994	0	0	147	46	15	209
1995	0	0	0	46	15	61

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
1996	0	0	1	46	15	62
1997	0	0	1	46	15	62
1998	0	0	1	46	15	62
1999	0	0	1	46	15	62
2000	0	0	1	46	15	63
2001	0	0	234	46	15	296
2002	0	0	0	46	15	61
2003	0	0	1	46	15	62
2004	0	0	1	46	15	62
2005	780	454	1	46	15	1296

----- PRESS A KEY FOR MORE -----

Figure C14. Facility Cost Report for REMR Policy 3 (Continued)

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2006	0	0	1	46	15	62
2007	0	0	1	46	15	62
2008	0	0	1	46	15	62
2009	0	0	1	46	15	63
2010	0	0	147	46	15	209
2011	0	0	0	46	15	61
2012	0	0	1	46	15	62
2013	0	0	1	46	15	62
2014	0	0	1	46	15	62
2015	0	0	1	46	15	63

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2016	0	0	1	46	15	63
2017	0	0	250	46	15	312
2018	0	0	0	46	15	61
2019	0	0	1	46	15	62
2020	3660	2618	1	46	15	6339
2021	0	0	1	46	15	62
2022	0	0	1	46	15	62
2023	0	0	1	46	15	62
2024	0	0	1	46	15	62
2025	0	0	1	46	15	63

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2026	0	0	147	46	15	209
2027	0	0	0	46	15	61
2028	0	0	1	46	15	62
2029	0	0	1	46	15	62
2030	0	0	1	46	15	62
2031	0	0	1	46	15	63
2032	0	0	1	46	15	63
2033	0	0	250	46	15	312
2034	0	0	0	46	15	61
2035	0	0	1	46	15	62
EUC.	30	20	16	44	15	125
TOT.	367	242	190	536	178	1512

Discount rate - 8.125%   Costs are in thousands of dollars

----- PRESS A KEY FOR MORE -----

Figure C14. (Concluded)

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	agency cost	user cost	total cost
1986	61	265	326
1987	62	289	351
1988	62	310	372
1989	62	329	391
1990	62	347	409
1991	62	364	426
1992	62	381	443
1993	62	398	460
1994	209	375	584
1995	61	370	431

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
1996	62	383	445
1997	62	395	457
1998	62	409	471
1999	62	423	485
2000	63	438	501
2001	296	1526	1822
2002	61	374	435
2003	62	385	447
2004	62	396	458
2005	1296	415	1711

----- PRESS A KEY FOR MORE -----

Figure C15. Facility Total Cost Report for REMR Policy 3 (Continued)

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2006	62	408	470
2007	62	421	483
2008	62	434	496
2009	63	448	511
2010	209	420	629
2011	61	410	471
2012	62	422	484
2013	62	436	498
2014	62	452	514
2015	63	469	532

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2016	63	488	551
2017	312	1575	1887
2018	61	418	479
2019	62	436	498
2020	6339	1559	7898
2021	62	391	453
2022	62	402	464
2023	62	412	474
2024	62	424	486
2025	63	437	500

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2026	209	407	616
2027	61	395	456
2028	62	405	467
2029	62	416	478
2030	62	428	490
2031	63	441	504
2032	63	455	518
2033	312	1540	1852
2034	61	375	436
2035	62	385	447
EUC.	125	394	519
TOT.	1512	4752	6264

Discount rate = 8.125% Costs are in thousands of dollars

----- PRESS A KEY FOR MORE -----

Figure C15. (Concluded)

```
name:                          P4
number:                        4
gate cond index std:           5.40
     time major:               40.00
     time minor:               25.00
     delta:                    0.45
     routine maint levels:
wall cond index std:           8.40
     time major:               40.00
     time minor:               25.00
     delta:                    0.20
     routine maint levels:
mech dev cond index std:       0.107
     time major:               18.00
     time minor:               10.00
     delta:                    0.024
     routine maint level:      5.00
```

```
ROUTINE MAINTAINENCE
Year 1986 Level 5.00
Year 0 Level 0.00
Year 0 Level 0.00
Year 0 Level 0.00
```

Figure C16. Windows describing REMR Policy 4

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
1986	5.00	9.70	0.12	5.00	9.70	0.10	9.95
1987	5.00	9.61	0.13	5.00	9.64	0.11	9.89
1988	5.00	9.55	0.13	5.00	9.61	0.11	9.85
1989	5.00	9.50	0.14	5.00	9.58	0.12	9.80
1990	5.00	9.44	0.15	5.00	9.55	0.12	9.76
1991	5.00	9.38	0.15	5.00	9.52	0.13	9.71
1992	5.00	9.32	0.16	5.00	9.49	0.13	9.65
1993	5.00	9.26	0.16	5.00	9.46	0.14	9.60
1994	5.00	9.19	0.17	5.00	9.43	0.14	9.53
1995	5.00	9.12	0.18	5.00	9.40	0.15	9.77

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
1996	5.00	9.04	0.18	5.00	9.37	0.15	9.71
1997	5.00	8.96	0.19	5.00	9.34	0.16	9.65
1998	5.00	8.88	0.20	5.00	9.31	0.17	9.60
1999	5.00	8.80	0.21	5.00	9.27	0.17	9.53
2000	5.00	8.70	0.22	5.00	9.24	0.18	9.47
2001	5.00	8.61	0.22	5.00	9.21	0.19	9.39
2002	5.00	8.51	0.23	5.00	9.17	0.19	9.31
2003	5.00	8.40	0.24	5.00	9.13	0.20	9.95
2004	5.00	8.29	0.25	5.00	9.10	0.21	9.89
2005	5.00	8.17	0.26	5.00	9.06	0.22	9.85

----- PRESS A KEY FOR MORE -----

Figure C17. Facility Condition Report for REMR Policy 4 (Continued)

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
2006	5.00	8.05	0.27	5.00	9.02	0.23	9.80
2007	5.00	7.92	0.28	5.00	8.98	0.24	9.76
2008	5.00	7.79	0.30	5.00	8.93	0.25	9.71
2009	5.00	7.65	0.31	5.00	8.89	0.26	9.65
2010	5.00	8.10	0.23	5.00	9.09	0.19	9.60
2011	5.00	7.92	0.24	5.00	9.06	0.20	9.53
2012	5.00	7.79	0.25	5.00	9.02	0.21	9.47
2013	5.00	7.65	0.26	5.00	8.98	0.22	9.71
2014	5.00	7.50	0.27	5.00	8.93	0.22	9.65
2015	5.00	7.35	0.28	5.00	8.89	0.23	9.60

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
2016	5.00	7.19	0.29	5.00	8.85	0.24	9.53
2017	5.00	7.02	0.30	5.00	8.80	0.25	9.47
2018	5.00	6.84	0.32	5.00	8.76	0.26	9.39
2019	5.00	6.66	0.33	5.00	8.71	0.27	9.31
2020	5.00	6.47	0.34	5.00	8.66	0.28	9.23
2021	5.00	6.27	0.36	5.00	8.61	0.30	9.95
2022	5.00	6.06	0.37	5.00	8.56	0.31	9.89
2023	5.00	5.85	0.38	5.00	8.50	0.32	9.85
2024	5.00	5.62	0.40	5.00	8.45	0.33	9.80
2025	5.00	9.80	0.12	5.00	9.80	0.10	9.76

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
2026	5.00	9.61	0.12	5.00	9.64	0.10	9.71
2027	5.00	9.55	0.13	5.00	9.61	0.11	9.65
2028	5.00	9.50	0.13	5.00	9.58	0.11	9.60
2029	5.00	9.44	0.14	5.00	9.55	0.12	9.53
2030	5.00	9.38	0.15	5.00	9.52	0.12	9.47
2031	5.00	9.32	0.15	5.00	9.49	0.13	9.71
2032	5.00	9.26	0.16	5.00	9.46	0.13	9.65
2033	5.00	9.19	0.16	5.00	9.43	0.14	9.60
2034	5.00	9.12	0.17	5.00	9.40	0.14	9.53
2035	5.00	9.04	0.18	5.00	9.37	0.15	9.47
AVE.	5.00	8.39	0.22	5.00	9.20	0.19	9.65

----- PRESS A KEY FOR MORE -----

Figure C17. (Concluded)

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
1986	4249.37	1.95	0.18	0.00	0.62
1987	4453.53	1.94	0.25	0.00	0.65
1988	4620.68	1.94	0.29	0.00	0.67
1989	4757.54	1.94	0.32	0.00	0.69
1990	4869.59	1.94	0.36	0.00	0.71
1991	4961.32	1.93	0.39	0.00	0.73
1992	5036.43	1.93	0.43	0.00	0.76
1993	5097.92	1.93	0.46	0.00	0.78
1994	5148.27	1.92	0.49	0.00	0.81
1995	5189.49	1.93	0.35	5.00	0.72

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
1996	5223.24	1.92	0.40	0.00	0.75
1997	5250.87	1.92	0.43	0.00	0.78
1998	5273.49	1.91	0.47	0.00	0.80
1999	5292.01	1.91	0.50	0.00	0.83
2000	5307.18	1.90	0.53	0.00	0.86
2001	5319.59	1.90	0.57	0.00	0.89
2002	5329.75	1.89	0.60	0.00	0.92
2003	5338.08	1.90	0.22	40.00	0.68
2004	5344.89	1.89	0.28	0.00	0.71
2005	5350.47	1.89	0.32	0.00	0.73

----- PRESS A KEY FOR MORE -----

Figure C18. Facility Service Report for REMR Policy 4 (Continued)

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2006	5355.04	1.88	0.35	0.00	0.75
2007	5358.78	1.87	0.39	0.00	0.78
2008	5361.84	1.85	0.42	0.00	0.81
2009	5364.34	1.84	0.46	0.00	0.83
2010	5366.40	1.88	0.47	5.00	0.83
2011	5368.08	1.86	0.50	0.00	0.86
2012	5369.45	1.85	0.54	0.00	0.89
2013	5370.58	1.84	0.41	5.00	0.81
2014	5371.50	1.83	0.45	0.00	0.84
2015	5372.26	1.81	0.48	0.00	0.87

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2016	5372.87	1.79	0.51	0.00	0.91
2017	5373.38	1.76	0.55	0.00	0.95
2018	5373.79	1.73	0.58	0.00	1.00
2019	5374.13	1.69	0.62	0.00	1.06
2020	5374.41	1.65	0.65	0.00	1.13
2021	5374.64	1.62	0.27	40.00	0.86
2022	5374.82	1.56	0.32	0.00	0.93
2023	5374.98	1.50	0.36	0.00	1.01
2024	5375.10	1.43	0.40	0.00	1.10
2025	5375.20	1.94	0.36	40.00	0.73

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2026	5375.29	1.94	0.39	0.00	0.75
2027	5375.36	1.94	0.42	0.00	0.77
2028	5375.41	1.93	0.46	0.00	0.79
2029	5375.46	1.93	0.49	0.00	0.82
2030	5375.50	1.93	0.52	0.00	0.84
2031	5375.53	1.93	0.39	5.00	0.75
2032	5375.55	1.93	0.43	0.00	0.77
2033	5375.57	1.92	0.46	0.00	0.80
2034	5375.59	1.92	0.49	0.00	0.82
2035	5375.60	1.92	0.53	0.00	0.85
AVE.	5251.40	1.86	0.43	3.70	0.82

Total expected but unscheduled down time is 1.14 days

----- PRESS A KEY FOR MORE -----

Figure C18. (Concluded)

MANAGEMENT SYSTEM FOR CIVIL WORKS   PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	gate rep	wall rep	mech rep	routine rep	damage	total
1986	0	0	0	33	15	48
1987	0	0	1	33	15	49
1988	0	0	1	33	15	49
1989	0	0	1	33	15	49
1990	0	0	1	33	15	49
1991	0	0	1	33	15	49
1992	0	0	1	33	15	49
1993	0	0	1	33	15	49
1994	0	0	1	33	15	49
1995	0	0	147	33	15	195

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
1996	0	0	0	33	15	48
1997	0	0	1	33	15	49
1998	0	0	1	33	15	49
1999	0	0	1	33	15	49
2000	0	0	1	33	15	49
2001	0	0	1	33	15	49
2002	0	0	1	33	15	49
2003	0	0	294	33	15	342
2004	0	0	0	33	15	48
2005	0	0	1	33	15	49

----- PRESS A KEY FOR MORE -----

Figure C19. Facility Cost Report for REMR Policy 4 (Continued)

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2006	0	0	1	33	15	49
2007	0	0	1	33	15	49
2008	0	0	1	33	15	49
2009	0	0	1	33	15	49
2010	780	454	1	33	15	1283
2011	0	0	1	33	15	49
2012	0	0	1	33	15	49
2013	0	0	147	33	15	195
2014	0	0	0	33	15	48
2015	0	0	1	33	15	49

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2016	0	0	1	33	15	49
2017	0	0	1	33	15	49
2018	0	0	1	33	15	49
2019	0	0	1	33	15	49
2020	0	0	1	33	15	49
2021	0	0	315	33	15	363
2022	0	0	0	33	15	48
2023	0	0	1	33	15	49
2024	0	0	1	33	15	49
2025	4770	3070	1	33	15	7888

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2026	0	0	1	33	15	49
2027	0	0	1	33	15	49
2028	0	0	1	33	15	49
2029	0	0	1	33	15	49
2030	0	0	1	33	15	49
2031	0	0	147	33	15	195
2032	0	0	0	33	15	48
2033	0	0	1	33	15	49
2034	0	0	1	33	15	49
2035	0	0	1	33	15	49
EUC.	24	15	15	31	15	99
TOT.	287	179	178	377	178	1199

Discount rate = 8.125%   Costs are in thousands of dollars

----- PRESS A KEY FOR MORE -----

Figure C19. (Concluded)

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	agency cost	user cost	total cost
1986	48	265	313
1987	49	290	339
1988	49	310	359
1989	49	330	379
1990	49	348	397
1991	49	366	415
1992	49	383	432
1993	49	401	450
1994	49	419	468
1995	195	395	590

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
1996	48	394	442
1997	49	409	458
1998	49	423	472
1999	49	439	488
2000	49	456	505
2001	49	474	523
2002	49	493	542
2003	342	1537	1879
2004	48	382	430
2005	49	393	442

----- PRESS A KEY FOR MORE -----

Figure C20. Facility Total Cost Report for REMR Policy 4 (Continued)

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2006	49	406	455
2007	49	419	468
2008	49	433	482
2009	49	449	498
2010	1283	463	1746
2011	49	462	511
2012	49	480	529
2013	195	453	648
2014	48	450	498
2015	49	469	518

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2016	49	489	538
2017	49	513	562
2018	49	540	589
2019	49	571	620
2020	49	607	656
2021	363	1644	2007
2022	48	503	551
2023	49	544	593
2024	49	594	643
2025	7888	1570	9458

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2026	49	403	452
2027	49	414	463
2028	49	427	476
2029	49	440	489
2030	49	454	503
2031	195	425	620
2032	48	417	465
2033	49	430	479
2034	49	444	493
2035	49	458	507
EUC.	99	401	500
TOT.	1199	4831	6030

Discount rate = 8.125%   Costs are in thousands of dollars

----- PRESS A KEY FOR MORE -----

Figure C20. (Concluded)

name:	P1
number:	6
gate cond index std:	2.10
time major:	49.00
time minor:	35.00
delta:	0.45
routine maint levels:	
wall cond index std:	7.70
time major:	49.00
time minor:	35.00
delta:	0.20
routine maint levels:	
mech dev cond index std:	0.184
time major:	22.00
time minor:	12.00
delta:	0.024
routine maint level:	3.00

ROUTINE MAINTAINENCE
Year 1986 Level 3.00
Year 0 Level 0.00
Year 0 Level 0.00
Year 0 Level 0.00

Figure C21. Windows describing REMR Policy 6

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
1986	3.00	9.70	0.13	3.00	9.70	0.11	9.95
1987	3.00	9.61	0.13	3.00	9.64	0.11	9.89
1988	3.00	9.55	0.14	3.00	9.61	0.12	9.84
1989	3.00	9.50	0.15	3.00	9.58	0.13	9.79
1990	3.00	9.44	0.16	3.00	9.55	0.13	9.74
1991	3.00	9.38	0.17	3.00	9.52	0.14	9.69
1992	3.00	9.32	0.18	3.00	9.49	0.15	9.63
1993	3.00	9.26	0.19	3.00	9.46	0.16	9.56
1994	3.00	9.19	0.20	3.00	9.43	0.17	9.49
1995	3.00	9.12	0.21	3.00	9.40	0.18	9.42

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

	GATE			WALL			MECH DEV
year	maint	c.i.	dev.	maint	c.i.	dev.	c.i.
1996	3.00	9.04	0.23	3.00	9.37	0.19	9.34
1997	3.00	8.96	0.24	3.00	9.34	0.20	9.58
1998	3.00	8.88	0.25	3.00	9.31	0.21	9.49
1999	3.00	8.80	0.27	3.00	9.27	0.22	9.42
2000	3.00	8.70	0.28	3.00	9.24	0.24	9.34
2001	3.00	8.61	0.30	3.00	9.21	0.25	9.25
2002	3.00	8.51	0.32	3.00	9.17	0.27	9.15
2003	3.00	8.40	0.34	3.00	9.13	0.28	9.04
2004	3.00	8.29	0.36	3.00	9.10	0.30	8.93
2005	3.00	8.17	0.38	3.00	9.06	0.32	8.81

----- PRESS A KEY FOR MORE -----

Figure C22. Facility Condition Report for REMR Policy 6 (Continued)

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	GATE maint	GATE c.i.	GATE dev.	WALL maint	WALL c.i.	WALL dev.	MECH DEV c.i.
2006	3.00	8.05	0.40	3.00	9.02	0.33	8.68
2007	3.00	7.92	0.43	3.00	8.98	0.35	9.95
2008	3.00	7.79	0.45	3.00	8.93	0.38	9.89
2009	3.00	7.65	0.48	3.00	8.89	0.40	9.84
2010	3.00	7.50	0.51	3.00	8.85	0.42	9.79
2011	3.00	7.35	0.54	3.00	8.80	0.45	9.74
2012	3.00	7.19	0.57	3.00	8.76	0.47	9.69
2013	3.00	7.02	0.60	3.00	8.71	0.50	9.63
2014	3.00	6.84	0.64	3.00	8.66	0.53	9.56
2015	3.00	6.66	0.67	3.00	8.61	0.56	9.49

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	GATE maint	GATE c.i.	GATE dev.	WALL maint	WALL c.i.	WALL dev.	MECH DEV c.i.
2016	3.00	6.47	0.71	3.00	8.56	0.59	9.42
2017	3.00	6.27	0.76	3.00	8.50	0.63	9.34
2018	3.00	6.06	0.80	3.00	8.45	0.67	9.25
2019	3.00	5.85	0.85	3.00	8.40	0.71	9.49
2020	3.00	6.30	0.64	3.00	8.60	0.53	9.42
2021	3.00	6.06	0.67	3.00	8.56	0.56	9.34
2022	3.00	5.85	0.71	3.00	8.50	0.59	9.25
2023	3.00	5.62	0.76	3.00	8.45	0.63	9.15
2024	3.00	5.39	0.80	3.00	8.40	0.67	9.04
2025	3.00	5.15	0.85	3.00	8.34	0.71	8.93

----- PRESS A KEY FOR MORE -----

CONDITION REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	GATE maint	GATE c.i.	GATE dev.	WALL maint	WALL c.i.	WALL dev.	MECH DEV c.i.
2026	3.00	4.89	0.90	3.00	8.28	0.75	8.81
2027	3.00	4.63	0.95	3.00	8.22	0.79	8.68
2028	3.00	4.36	1.01	3.00	8.16	0.84	8.54
2029	3.00	4.07	1.07	3.00	8.10	0.89	9.95
2030	3.00	3.78	1.13	3.00	8.03	0.94	9.89
2031	3.00	3.47	1.20	3.00	7.97	1.00	9.84
2032	3.00	3.15	1.27	3.00	7.90	1.06	9.79
2033	3.00	2.82	1.34	3.00	7.83	1.12	9.74
2034	3.00	9.80	0.12	3.00	9.80	0.10	9.69
2035	3.00	9.61	0.13	3.00	9.64	0.11	9.63
AVE.	3.00	7.28	0.53	3.00	8.89	0.44	9.46

----- PRESS A KEY FOR MORE -----

Figure C22. (Concluded)

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
1986	4249.37	1.95	0.18	0.00	0.62
1987	4453.53	1.94	0.25	0.00	0.65
1988	4620.68	1.94	0.30	0.00	0.67
1989	4757.54	1.94	0.33	0.00	0.69
1990	4869.59	1.93	0.37	0.00	0.72
1991	4961.32	1.93	0.41	0.00	0.74
1992	5036.43	1.93	0.44	0.00	0.77
1993	5097.92	1.93	0.48	0.00	0.80
1994	5148.27	1.92	0.52	0.00	0.83
1995	5189.49	1.92	0.55	0.00	0.86

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
1996	5223.24	1.91	0.59	0.00	0.90
1997	5250.87	1.92	0.48	5.00	0.81
1998	5273.49	1.91	0.53	0.00	0.85
1999	5292.01	1.91	0.56	0.00	0.88
2000	5307.18	1.90	0.60	0.00	0.92
2001	5319.59	1.89	0.64	0.00	0.96
2002	5329.75	1.88	0.68	0.00	1.00
2003	5338.08	1.87	0.72	0.00	1.05
2004	5344.89	1.86	0.76	0.00	1.10
2005	5350.47	1.85	0.80	0.00	1.16

----- PRESS A KEY FOR MORE -----

Figure C23. Facility Service Report for REMR Policy 6 (Continued)

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2006	5355.04	1.84	0.85	0.00	1.22
2007	5358.78	1.87	0.30	40.00	0.73
2008	5361.84	1.86	0.36	0.00	0.77
2009	5364.34	1.84	0.40	0.00	0.80
2010	5366.40	1.83	0.44	0.00	0.83
2011	5368.08	1.81	0.48	0.00	0.87
2012	5369.45	1.79	0.52	0.00	0.91
2013	5370.58	1.76	0.56	0.00	0.96
2014	5371.50	1.73	0.61	0.00	1.02
2015	5372.26	1.69	0.65	0.00	1.09

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2016	5372.87	1.65	0.69	0.00	1.16
2017	5373.38	1.60	0.74	0.00	1.26
2018	5373.79	1.55	0.78	0.00	1.37
2019	5374.13	1.49	0.72	5.00	1.35
2020	5374.41	1.61	0.66	5.00	1.16
2021	5374.64	1.55	0.71	0.00	1.27
2022	5374.82	1.49	0.75	0.00	1.39
2023	5374.98	1.41	0.80	0.00	1.54
2024	5375.10	1.33	0.85	0.00	1.73
2025	5375.20	1.25	0.89	0.00	1.98

----- PRESS A KEY FOR MORE -----

SERVICE REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	traffic (tows)	srv rate (tows/hr)	std dev (hrs/tow)	shed down time (days)	ave delay (hrs/tow)
2026	5375.29	1.15	0.94	0.00	2.31
2027	5375.36	1.06	1.00	0.00	2.77
2028	5375.41	0.97	1.05	0.00	3.43
2029	5375.46	0.90	0.67	40.00	3.01
2030	5375.50	0.82	0.73	0.00	4.10
2031	5375.53	0.75	0.78	0.00	6.05
2032	5375.55	0.69	0.84	0.00	10.48
2033	5375.57	0.64	0.89	0.00	12.56*
2034	5375.59	1.94	0.40	40.00	0.75
2035	5375.60	1.94	0.44	0.00	0.78
AVE.	5251.40	1.64	0.61	3.60	1.73

Total expected but unscheduled down time is 2.04 days

----- PRESS A KEY FOR MORE -----

Figure C23. (Concluded)

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	gate rep	wall rep	mech rep	routine rep	damage	total
1986	0	0	0	13	15	28
1987	0	0	1	13	15	29
1988	0	0	1	13	15	29
1989	0	0	1	13	15	29
1990	0	0	1	13	15	29
1991	0	0	1	13	15	29
1992	0	0	1	13	15	29
1993	0	0	1	13	15	29
1994	0	0	1	13	15	29
1995	0	0	1	13	15	29

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
1996	0	0	1	13	15	29
1997	0	0	147	13	15	175
1998	0	0	0	13	15	28
1999	0	0	1	13	15	29
2000	0	0	1	13	15	29
2001	0	0	2	13	15	30
2002	0	0	2	13	15	30
2003	0	0	2	13	15	30
2004	0	0	2	13	15	30
2005	0	0	2	13	15	30

----- PRESS A KEY FOR MORE -----

Figure C24. Facility Cost Report for REMR Policy 6 (Continued)

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2006	0	0	2	13	15	30
2007	0	0	453	13	15	481
2008	0	0	0	13	15	28
2009	0	0	1	13	15	29
2010	0	0	1	13	15	29
2011	0	0	1	13	15	29
2012	0	0	1	13	15	29
2013	0	0	1	13	15	29
2014	0	0	1	13	15	29
2015	0	0	1	13	15	29

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2016	0	0	1	13	15	29
2017	0	0	1	13	15	29
2018	0	0	2	13	15	30
2019	0	0	147	13	15	175
2020	780	454	0	13	15	1262
2021	0	0	1	13	15	29
2022	0	0	2	13	15	30
2023	0	0	2	13	15	30
2024	0	0	2	13	15	30
2025	0	0	2	13	15	30

----- PRESS A KEY FOR MORE -----

REPAIR COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	gate rep	wall rep	mech rep	routine rep	damage	total
2026	0	0	2	13	15	30
2027	0	0	2	13	15	30
2028	0	0	2	13	15	30
2029	0	0	488	13	15	516
2030	0	0	0	13	15	28
2031	5	0	1	13	15	34
2032	4	0	1	13	15	32
2033	8	0	1	13	15	37
2034	7321	3990	1	13	15	11340
2035	0	0	1	13	15	29
EUC.	15	8	14	12	15	64
TOT.	182	101	166	147	178	774

Discount rate = 8.125% Costs are in thousands of dollars

----- PRESS A KEY FOR MORE ----

Figure C24. (Concluded)

MANAGEMENT SYSTEM FOR CIVIL WORKS PAGE 1

Developed for U. S. Army Construction Engineering Research Laboratory
by MIT Center for Construction Research and Engineering

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1

year	agency cost	user cost	total cost
1986	28	265	293
1987	29	290	319
1988	29	312	341
1989	29	332	361
1990	29	351	380
1991	29	370	399
1992	29	389	418
1993	29	408	437
1994	29	428	457
1995	29	448	477

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
1996	29	470	499
1997	175	445	620
1998	28	447	475
1999	29	467	496
2000	29	487	516
2001	30	510	540
2002	30	534	564
2003	30	560	590
2004	30	589	619
2005	30	620	650

----- PRESS A KEY FOR MORE -----

Figure C25. Facility Total Cost Report for REMR Policy 6 (Continued)

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2006	30	654	684
2007	481	1569	2050
2008	28	413	441
2009	29	430	459
2010	29	449	478
2011	29	469	498
2012	29	493	522
2013	29	519	548
2014	29	550	579
2015	29	586	615

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2016	29	627	656
2017	29	677	706
2018	30	737	767
2019	175	746	921
2020	1262	646	1908
2021	29	683	712
2022	30	749	779
2023	30	830	860
2024	30	933	963
2025	30	1066	1096

----- PRESS A KEY FOR MORE -----

TOTAL COST REPORT BY YEAR FOR DASHIELDS UNDER POLICY P1 (cont.)

year	agency cost	user cost	total cost
2026	30	1245	1275
2027	30	1491	1521
2028	30	1847	1877
2029	516	2796	3312
2030	28	2203	2231
2031	34	3252	3286
2032	32	5635	5667
2033	37	6751	6788
2034	11340	1584	12924
2035	29	419	448
EUC.	64	469	533
TOT.	774	5655	6429

Discount rate = 8.125%   Costs are in thousands of dollars

----- PRESS A KEY FOR MORE -----

Figure C25. (Concluded)

APPENDIX D: MENU DESCRIPTION FOR THE PROTOTYPE REMR MANAGEMENT SYSTEM

TITLE PAGE
(Press Any Key)
TOP MENU

SELECT: edit | run | report (displays all the reports) | quit

SELECT: update | add (not implemented yet) | set run parameters | predict (wait until finished running) | save modified data | return to program | exit to DOS

SELECT: locks and dams | maintenance policies

What lock would you like to modify? _____
(Enter Only one of the following lock names:

PIKEI
CUMBE
MONTG
DASH1
EMSW0

and then hit return)

What policy would you like to modify? _____
(Enter only one of the following policy names:

P1
P2
P3

and then hit return)

(The following categories of information are displayed on subsidiary windows:

edit history:	Select this to edit historical data
edit deterioration model:	Select this to edit deterioration model parameters
edit traffic/capacity:	Select this to edit traffic/capacity model parameters)

(Use up and down cursor keys to get to the desired parameter and then edit it by using right cursor, left cursor and del keys. To get the window to set routine maintenance levels for gate or wall, move the cursor to the corresponding row and then hit return. If desired, the user can set up to four different sets of routine maintenance levels for gates and for walls over the planning horizon. The user can do that by inputting the years when the new routine maintenance level starts and the new routine maintenance level for each of the four rows in the window. If the user desires to set only one routine maintenance level for the entire planning horizon, he/she can do that by inputting the beginning year and the routine maintenance level in the first row and by leaving the other three rows with zero values.)

NOTES:
1. Use Esc key to go back to previous menu level
2. Use up and down cursor keys to get to the option desired and then hit return to select the option
3. Use ^K - to delete everything from the cursor to the end of the field value (^ is used to denote ctrl key)
   ^U - to delete the field value and put the default field value
   ^Y - to display help menu
   ^X - to display general menu
4. All the text in parenthesis are brief instructions to the user.